Low Level RF Control System

Brian Chase

DOE Independent Project Review of PIP-II

15 November 2016

Brian Chase - Fermilab

Charge #1

- SPM – Low Level RF and RF Integration
- Started at Fermilab in 1982 and have work experience in cryogenics, power supplies, D0 detector electronics and beam Instrumentation
- LLRF – Linac, Main Injector, Tevatron, Recycler Ring
- SRF LLRF – Proton Driver, ILC, ILCTA, DESY (9mA Tests)
- LCLS-II, CMTS, PIP-II

- LLRF Team
  - AD LLRF - E. Cullerton, P. Varghese, J. Edelen, J. Einstein-Curtis, D. Klepec
  - IIFC - G. Joshi, S. Khole, D. Sharma, & many others
  - CSU – A. Edelen

Outline

- Project Status
- System overview
- Simulation and Results

Project Status

LLRF Systems needed to meet R&D Goals

- 325 MHz Horizontal test stand
  - Support for CW and pulsed mode (Operational)
- 650 MHz Horizontal test stands
  - Support for CW and pulsed mode operation(To be supplied by India)
- PIP2-IT
  - Master Oscillator and Phase Reference distribution line
    - 162.5 MHz & 325 MHz (Operational)
  - RFQ – 162.5 MHz (Q4FY15)
    - 2 RF amplifier system (Operational in pulsed and CW modes)
  - Buncher - 3 cavities - 162.5 MHz (1st buncher operational)
  - Half Wave Resonators - 8 cavities @162.5 MHz
  - SSR1 - 8 cavities @ 325 MHz
  - Kicker waveform generator

Synergy Between LLRF DOE Projects at FNAL

	RF Converters	Digital controller	Algorithms FW/SW	Phase Reference Line	Resonance Control
NML-ILC	FNAL v1,v2	FNAL MFC	FNAL v1	FNAL v1	Development
PIP2 IT HTS	v3	SOC-MFC	FNAL ongoing	in development	
CMTS-1	v3	SOC-MFC	FNAL ongoing	simplified	
LCLS-II 1.3 GHz	FNAL v4	LBNL	LBNL	SLAC	JLAB/FNAL
PIP2 IIFC HTS1, HTS2	v5	leveraged from LCLS-II	Leveraged	Leveraged	Leveraged
Mu2e G-2		SOC-MFC			

Lots of good project cross pollination going on

IIFC Deliverable Schedule

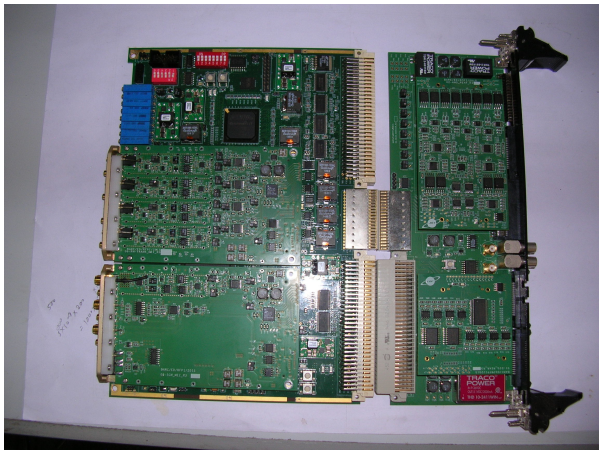
	Q1-16	Q2-16	Q3-16	Q4-16	Q1-17	Q2-17	Q3-17	Q4-17	Q1-18	Q2-18	Q3-18	Q4-18	Q1-19	Q2-19
RF Interlock														
Design and Certification 2 DAE	★													
Certification at FNAL				★										
RFPI for HTS2								★						
RFPI for SSR1											★			
RF Power system Ready for 1st SSR1 Cryomodule/HTS2												★		
RFPI for HB650													★	
LLRF System														
Initial Design of the System					★									
Prototype and Certification									★					
LLRF for HTS2										★				
LLRF for SSR1											★			
RF Power system Ready for 1st SSR1 Cryomodule/HTS2												★		
LLRF for HB650														★

★ Fermilab Milestone
★ DAE Milestone
+6 Months of schedule Contingency included in FY18 and 19 deliverables

A prototype RF protection and interlock has been delivered and tested at Fermilab

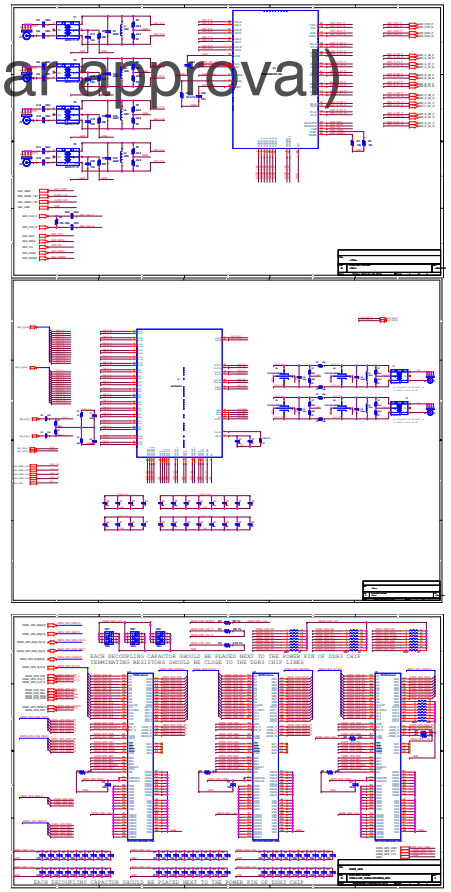
LLRF is on a reasonable pace for 2018 delivery

RFPI boards



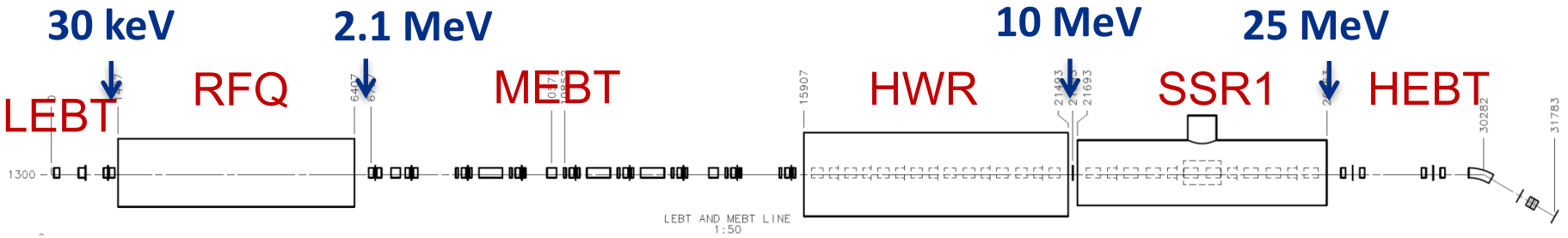
IIFC LLRF Status

- Seven joints FRSs Approved (two more near approval)
  - TRSs in process
- 8-Channel Down-Converters
  - BARC version is in manufacturing process
- 4-Channel Up-Converters
  - FNAL version tested
  - BARC version is in manufacturing process
- FPGA Board
  - In schematic review process
- ADC-DAC FMC Module
  - Ready for manufacturing
- Resonance Control Chassis
  - Leverage from FNAL LCLS-II design and is in progress



LLRF System Overview

PIP2-IT Low Level RF



- Drive 20 accelerating structures
- 3 RF frequencies
- Master Oscillator and phase reference lines
- 0.01% amplitude and 0.01 deg. Phase regulation goal

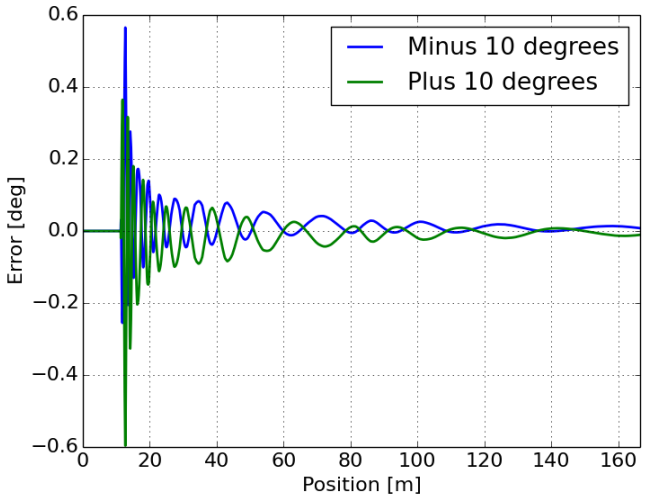
Cavity RF operating parameters

#	Frequency (MHz)	Section	Amplitude (MV)	Synchronous Phase (deg)	Pg(kW)
1	162.5	MEBT	0.088	-90	2.67
2	162.5	MEBT	0.065	-90	1.45
3	162.5	MEBT	0.079	-90	2.13
4	162.5	HWR	0.44	-48.06	0.325
5	162.5	HWR	0.7	-35	0.789
6	162.5	HWR	0.85	-33.95	1.155
7	162.5	HWR	1	-26	1.618
8	162.5	HWR	1.5	-24.03	3.312
9	162.5	HWR	1.5	-20.02	3.351
10	162.5	HWR	1.6	-22	3.724
11	162.5	HWR	1.7	-23.98	4.105
12	325	SSR1	1	-32.96	0.904
13	325	SSR1	1	-29.99	0.946
14	325	SSR1	1.1	-28.01	1.127
15	325	SSR1	1.25	-27.03	1.399
16	325	SSR1	1.5	-26.03	1.89
17	325	SSR1	1.5	-27.01	1.915
18	325	SSR1	1.5	-25	1.956
19	325	SSR1	2.2	-23.98	3.622
20	243.75	HEBT	1.07*	n/a	2.9

Primary Technical Risks

- Resonance and Field Control for 5 new cavity designs
  - Lorentz Force Detuning compensation for narrow bandwidth cavities operated in pulsed mode
  - New cavity designs with new mechanical properties
  - ~20 Hz half BW with expected 420 Hz Lorentz Force Detuning in SSR1
  - See resonance control talk
- 10^{-4} beam energy regulation with pulsed system
  - Sensitivity analysis in progress

RMS phase along LINAC from 10 deg cavity phase change in first HWR



RF Power budget and QI

Table 2.10: Requirements to RF power*

CM type	Power transferred to beam per cav. (kW)	Microphonics amplitude (Hz)	Cavity half-bandwidth, $f/2Q_L$, (Hz)	Power transfer efficiency	Power margin	Peak RF power per cavity (kW)
HWR	4	20	33	90%	80%	6.5
SSR1	4.1	20	43	90%	80%	6.1
SSR2	10	20	28	90%	80%	17
LB 650	23.8	20	29	94%	80%	38
HB 650	39.8	20	29	94%	80%	64

* Powers are computed for beam current of 2 mA. Allowances for transmission loss and microphonics suppression are included for the peak RF power.
♦ Microphonics amplitude represents a target value for maximum cavity detuning due to microphonics.

Total cavity detuning budget including LFD

Measured LFD is 22 times larger than the entire resonance error budget

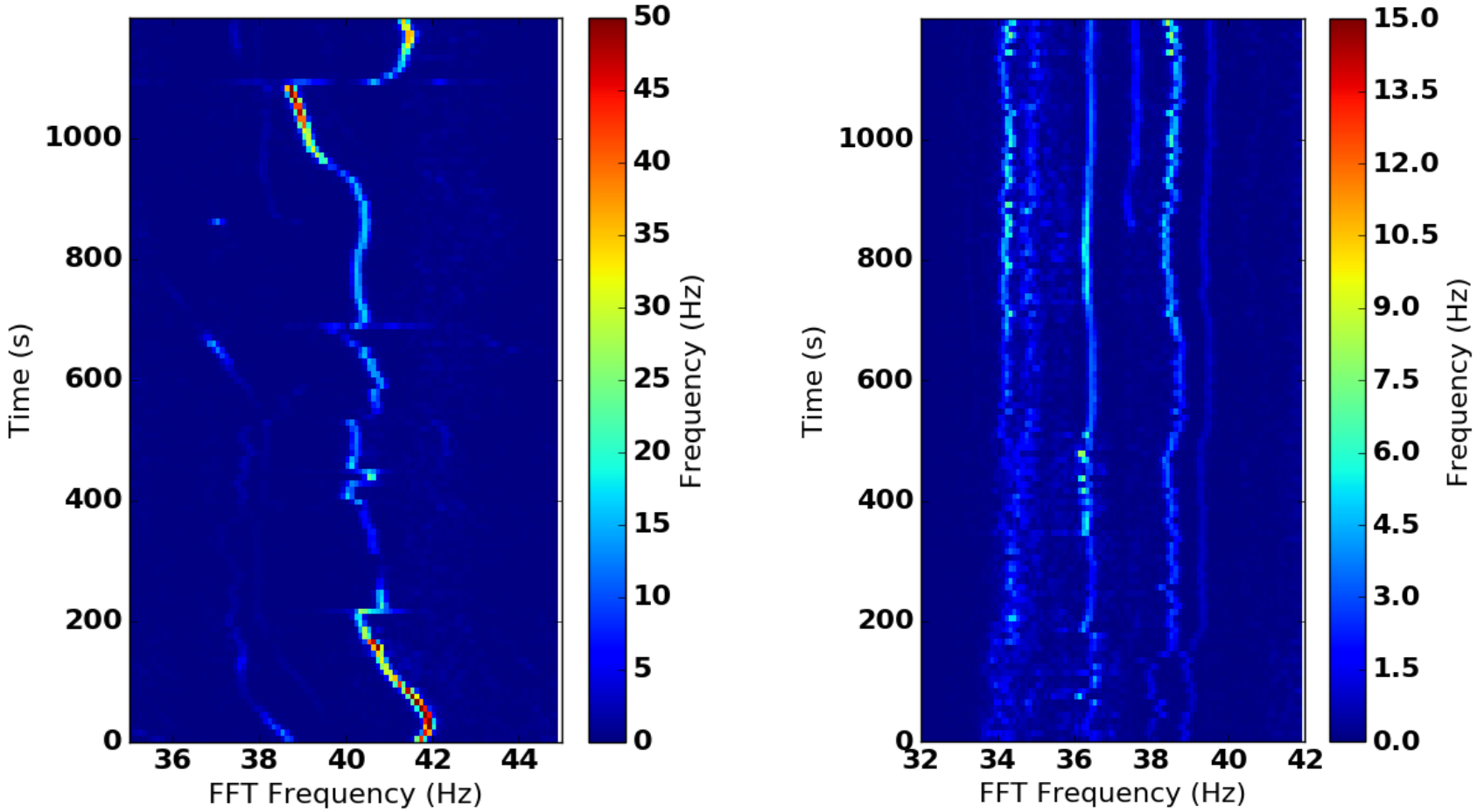
Table 2.11: Functional requirement specifications to cavity detuning due to helium pressure variations and Lorentz force detuning

CM type	HWR	SSR1	SSR2	LB650	HB650
Sensitivity to He pressure (FRS), df/dP , Hz/Torr	<25	<25	<25	<25	<25
… (measurements), df/dP , Hz/Torr	13	4.0	-	-	-
Estimated LFD sensitivity, df/dE^2, Hz/(MV/m)^2	-	-5.0	-	-0.8	-0.5
… (measurements), df/dE^2, Hz/(MV/m)^2	-1.5♦	-4.4	-	-	-
Estimated LFD at nominal voltage (FRS), Hz	-	-500	-	-192	-136
… (measurements) at nominal voltage, Hz	-122.4	-440	-	-	-

May need real-time feedback during pulse

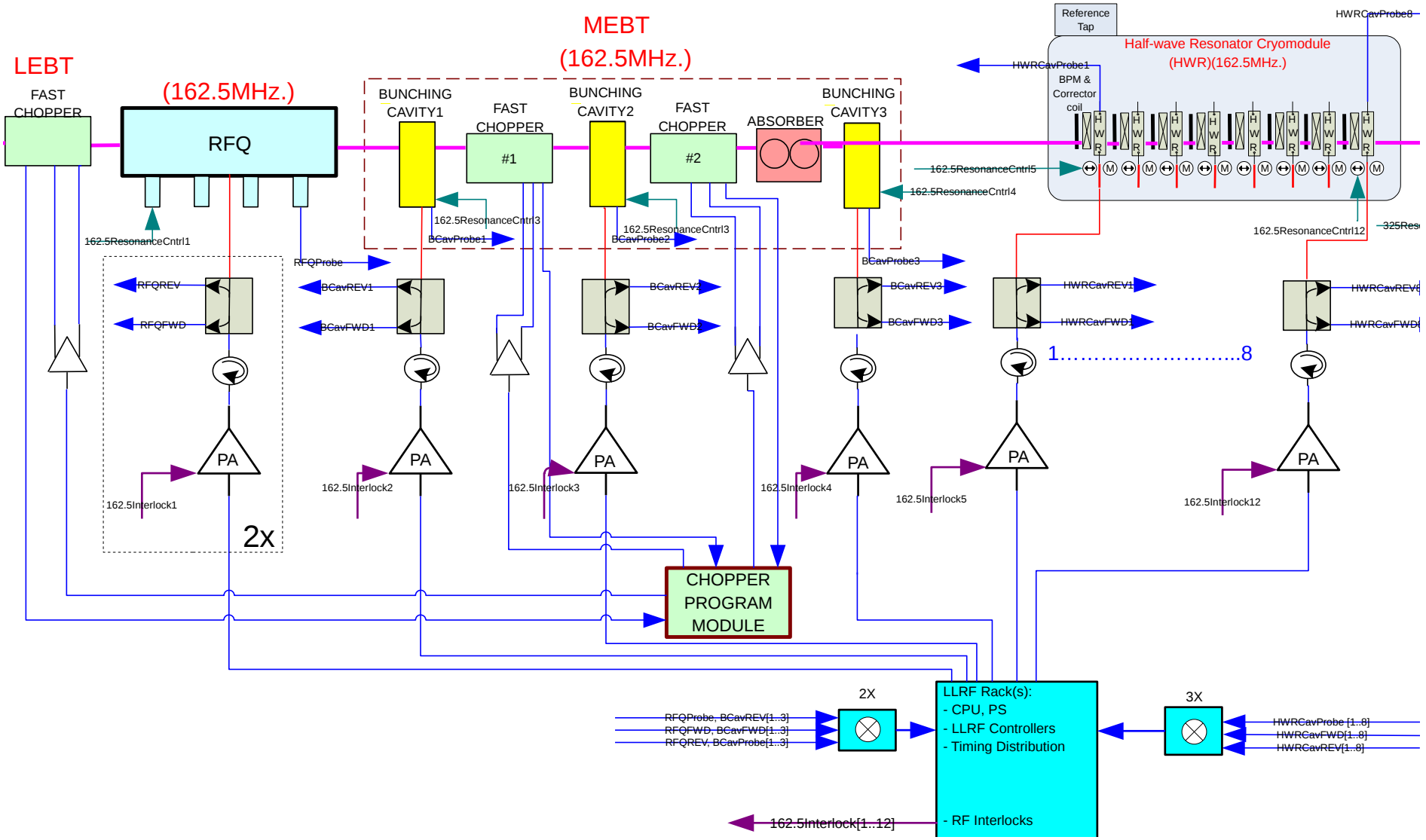
Ongoing cavity design efforts to lower these numbers

Example of Microphonic Detuning at CMTS-1

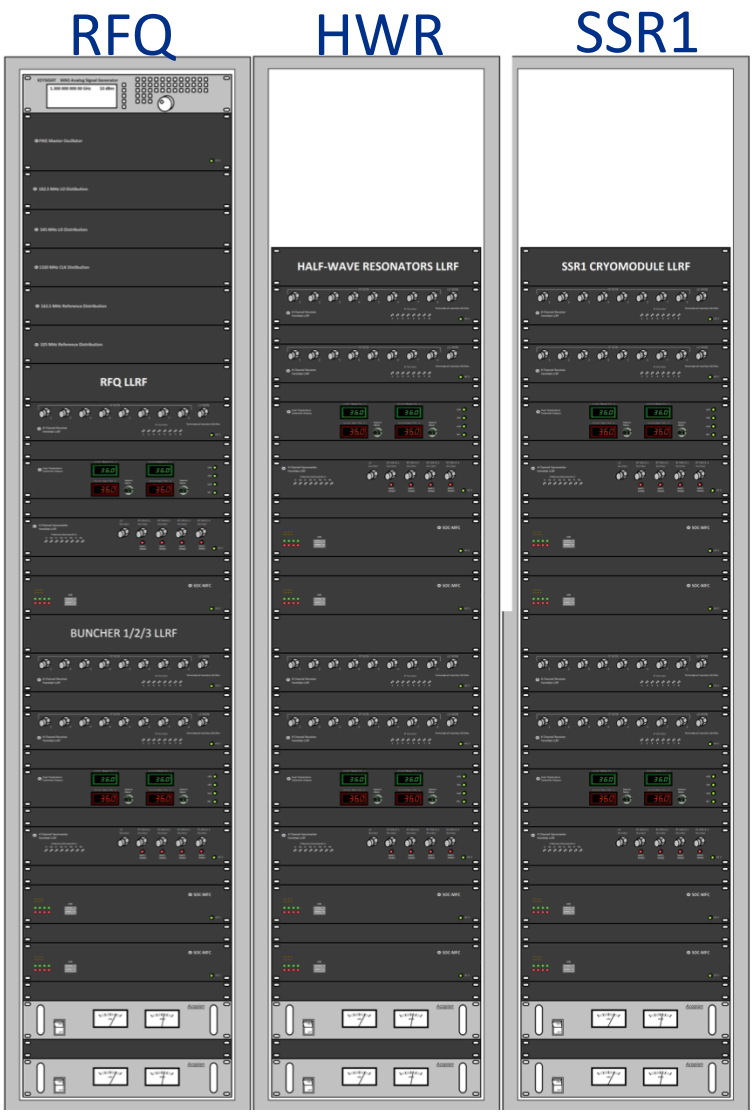


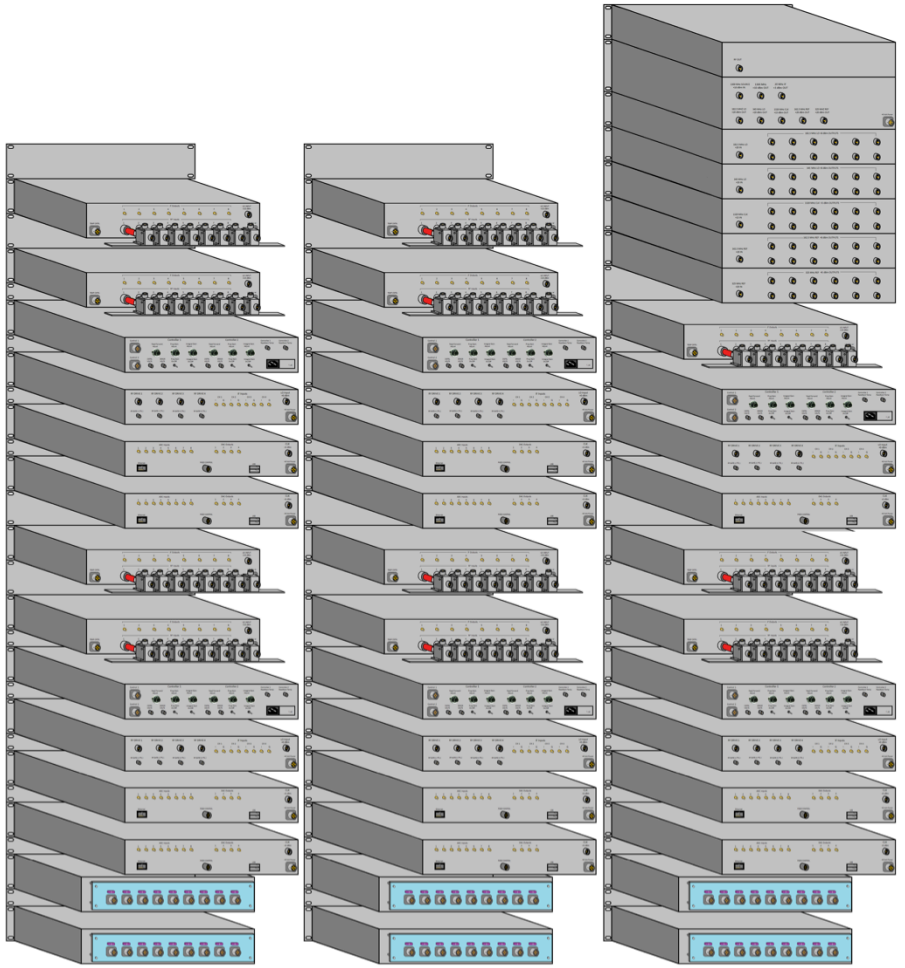
Main source is believed to be pressure fluctuation from a check valve in the helium return line and will be fixed in current shutdown. Resonance control is every system's responsibility.

PIP2-IT RF Stations Diagram

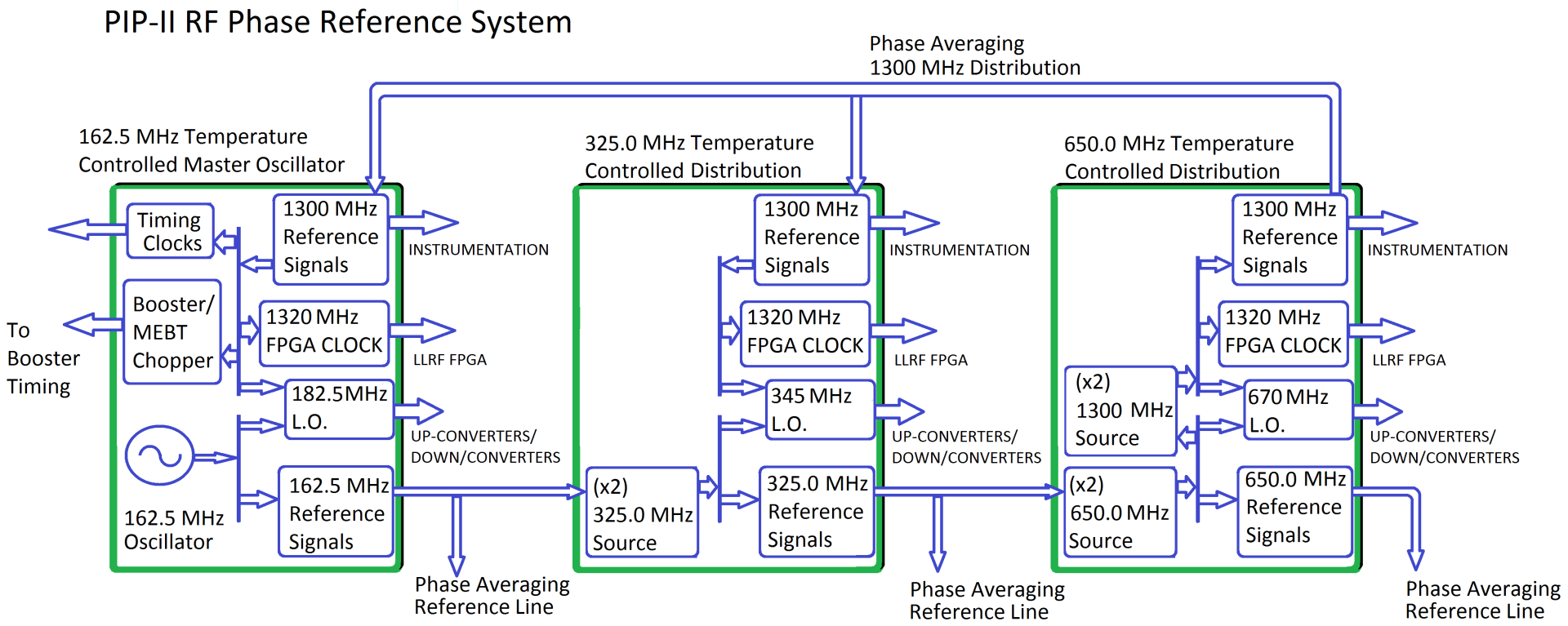


PIP2IT LLRF rack layout - front and rear view



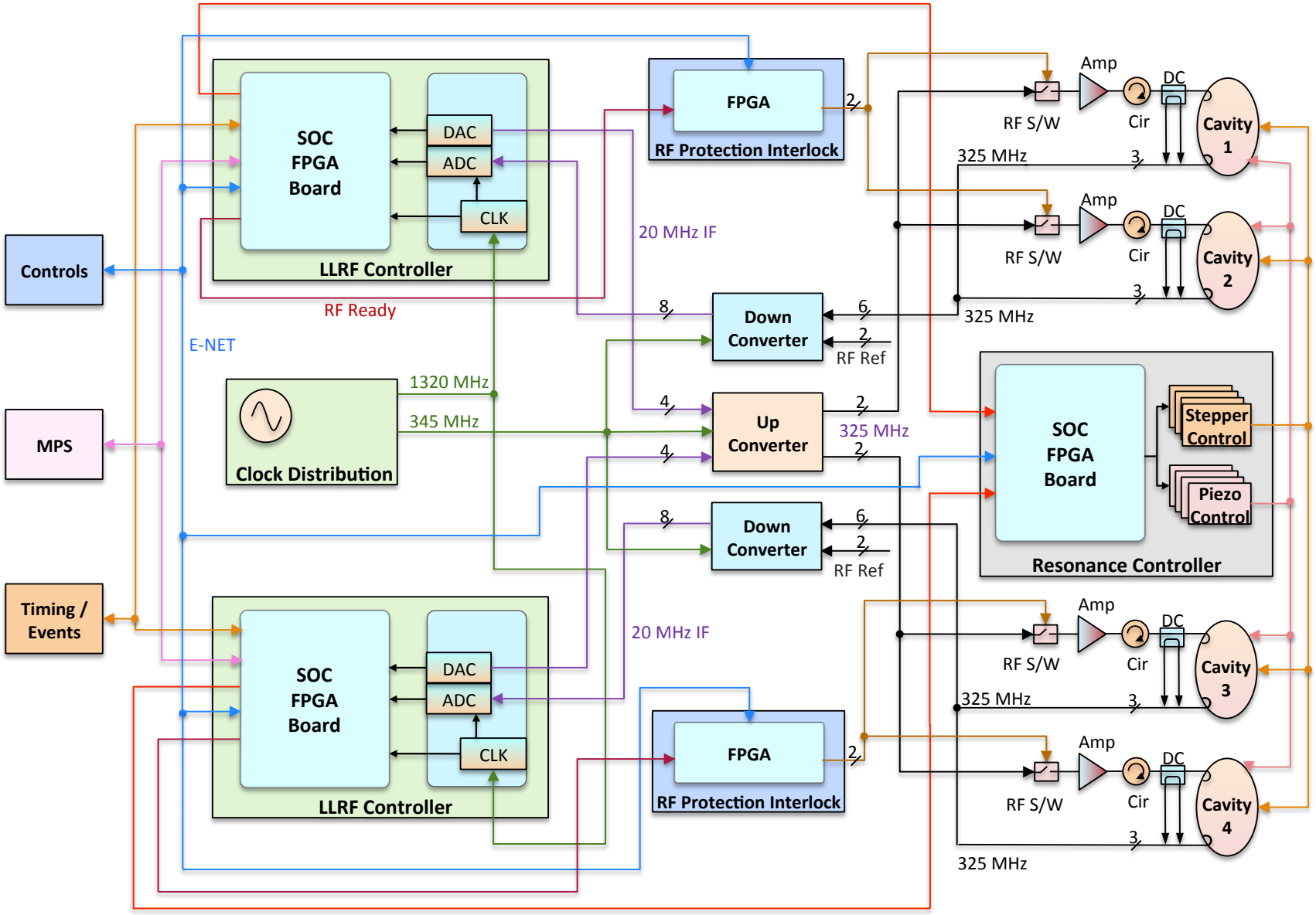


Phase Reference Lines (162.5, 325, 650 ,1300 MHz)



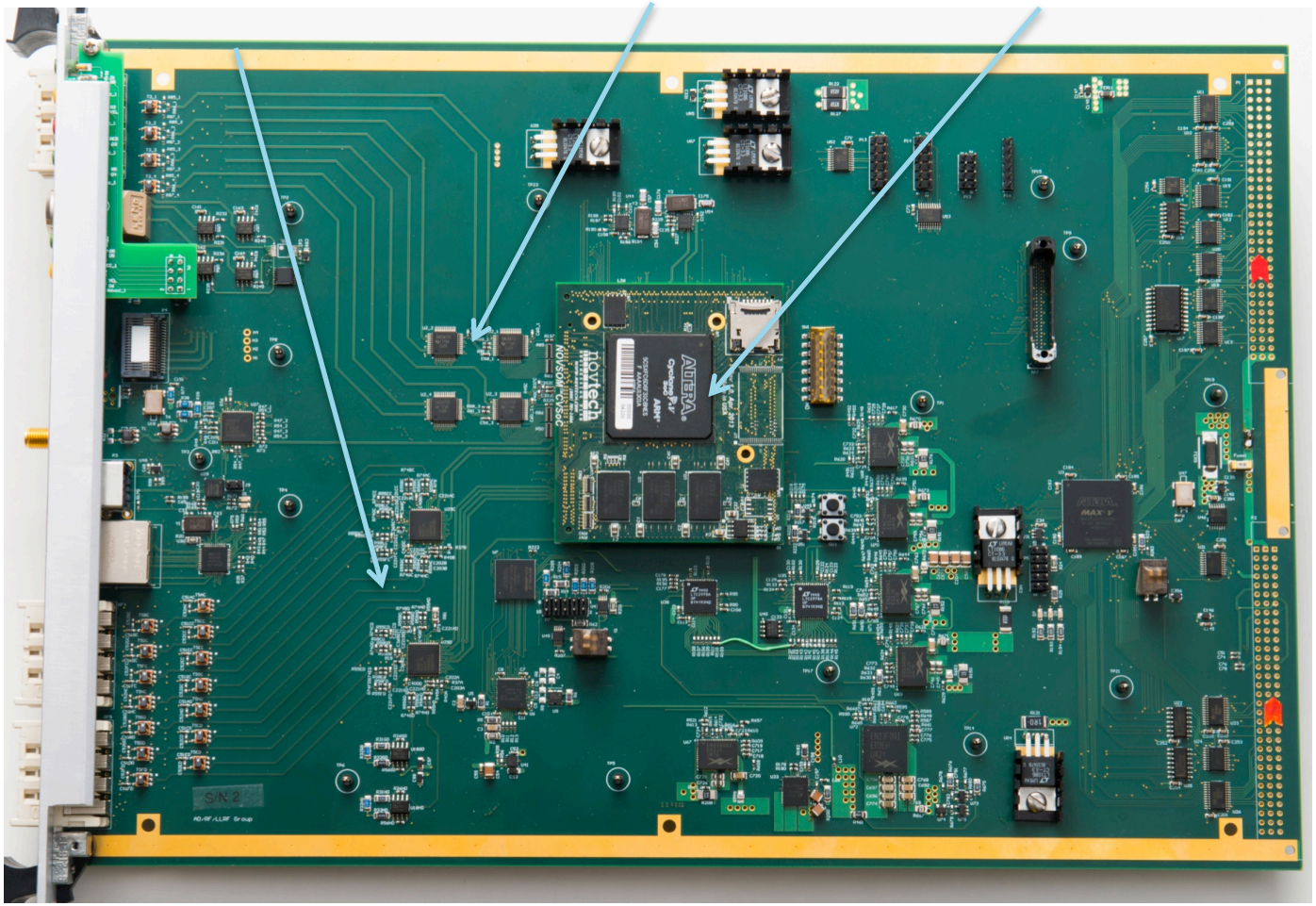
Multi-frequency Phase References and Local Oscillators

Basic LLRF Station Diagram for 4 cavities



System on Chip Multi-channel Field Controller

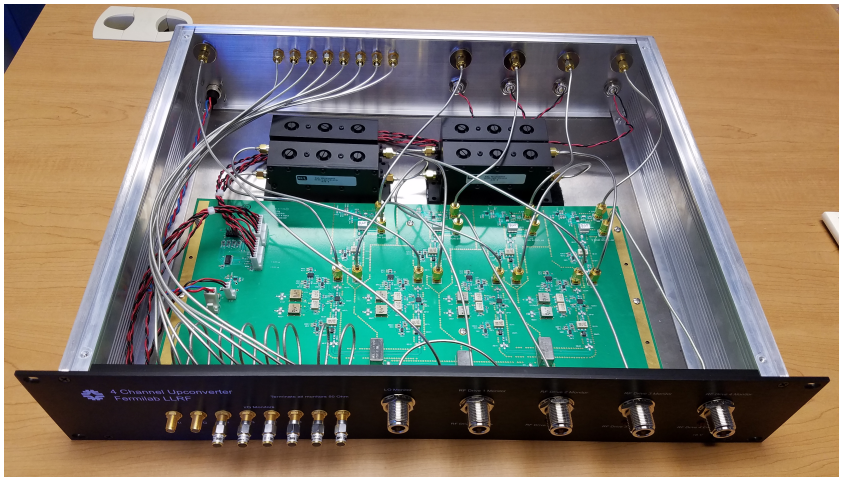
(16) 14 bit ADCs (8)14 bit DACs System on Module

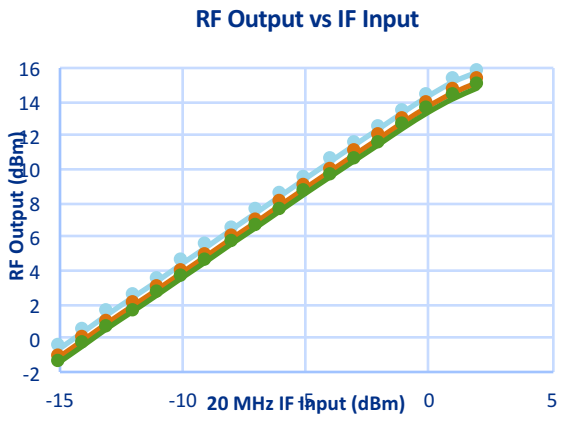


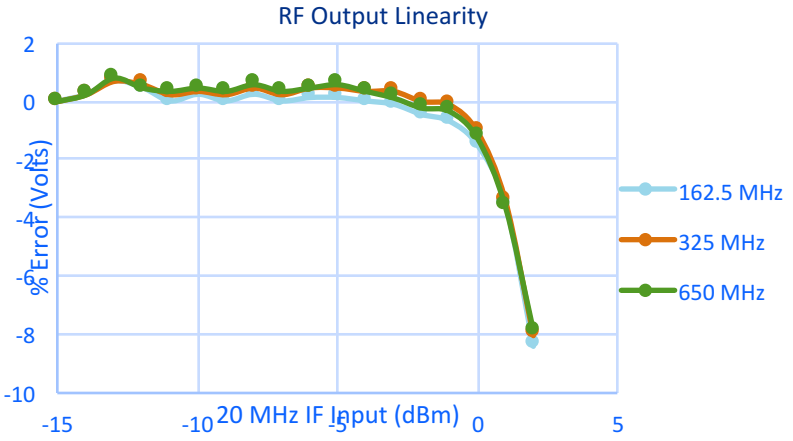
Dual core Arm processor with FPGA eliminates the need for a backplane and CPU card

4-Channel Up-converter

- 20 MHz IF input -2 dBm max
- 162.5, 325, and 650 MHz Output, +11 dBm max
- 13 dB IF to RF Conversion Gain typ.
- Channel to Channel Isolation > 88 dB
- Spurious Signal Suppression > 80 dB
- High isolation (>68 dB) TTL RF switch
- Power Supply 6V, 1.8 Amp

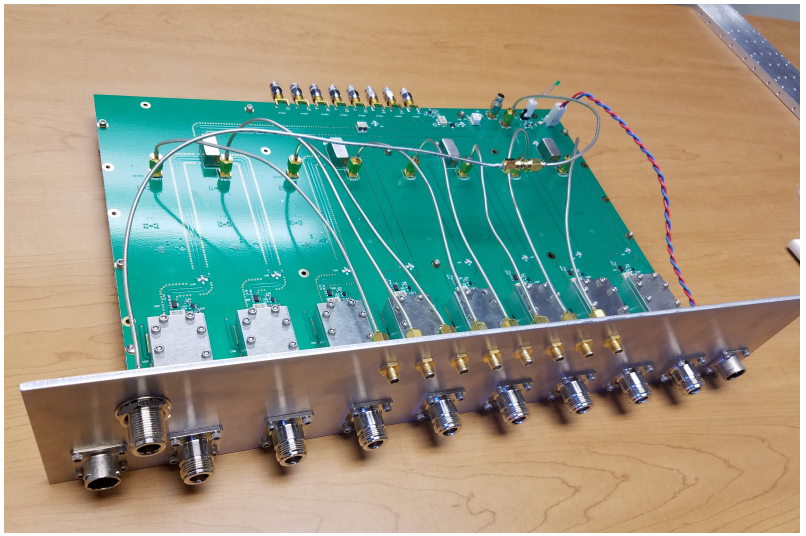


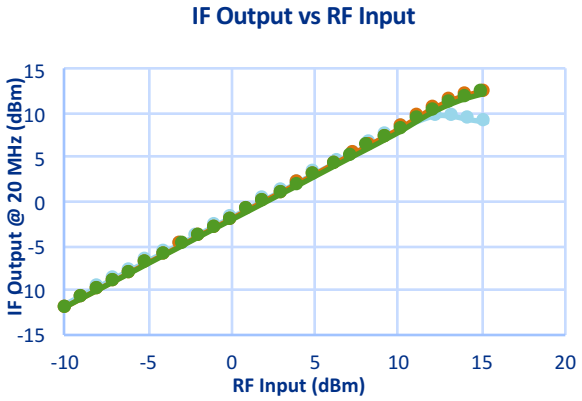


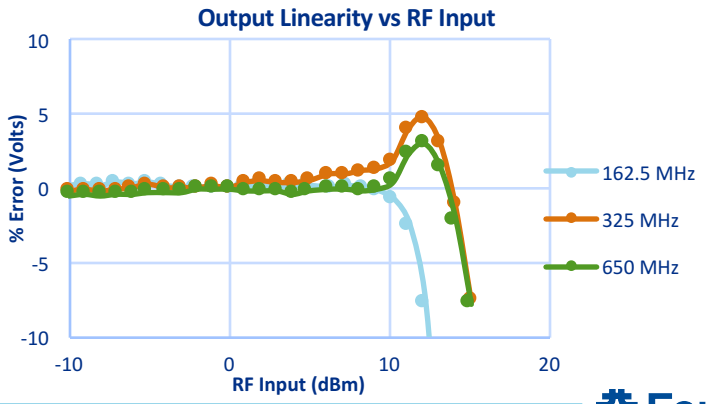


PIP-II LLRF 8-Channel Downconverter Prototype

- RF input 162.5 MHz – 650 MHz
- Less than 1% non-linearity up to 10 dBm RF input
- 1.8, 2.1, 2 dB conversion loss @ 162.5, 325, 650 MHz respectively
- Better than 82 dB Channel to Channel Isolation
- RF, LO, IF monitor ports
- Absorptive IF output low pass filter
- Noise output floor of -161 dBc/sqrt(Hz)
- Integrated output 1/f noise < 1.84 fsec, (0.02 to 20 Hz)
- LO Input power of 3.1, 3.8, and 5.7 dBm @ 162.5, 325, 650 MHz respectively
- Power Supply 6V, 2.25 Amps



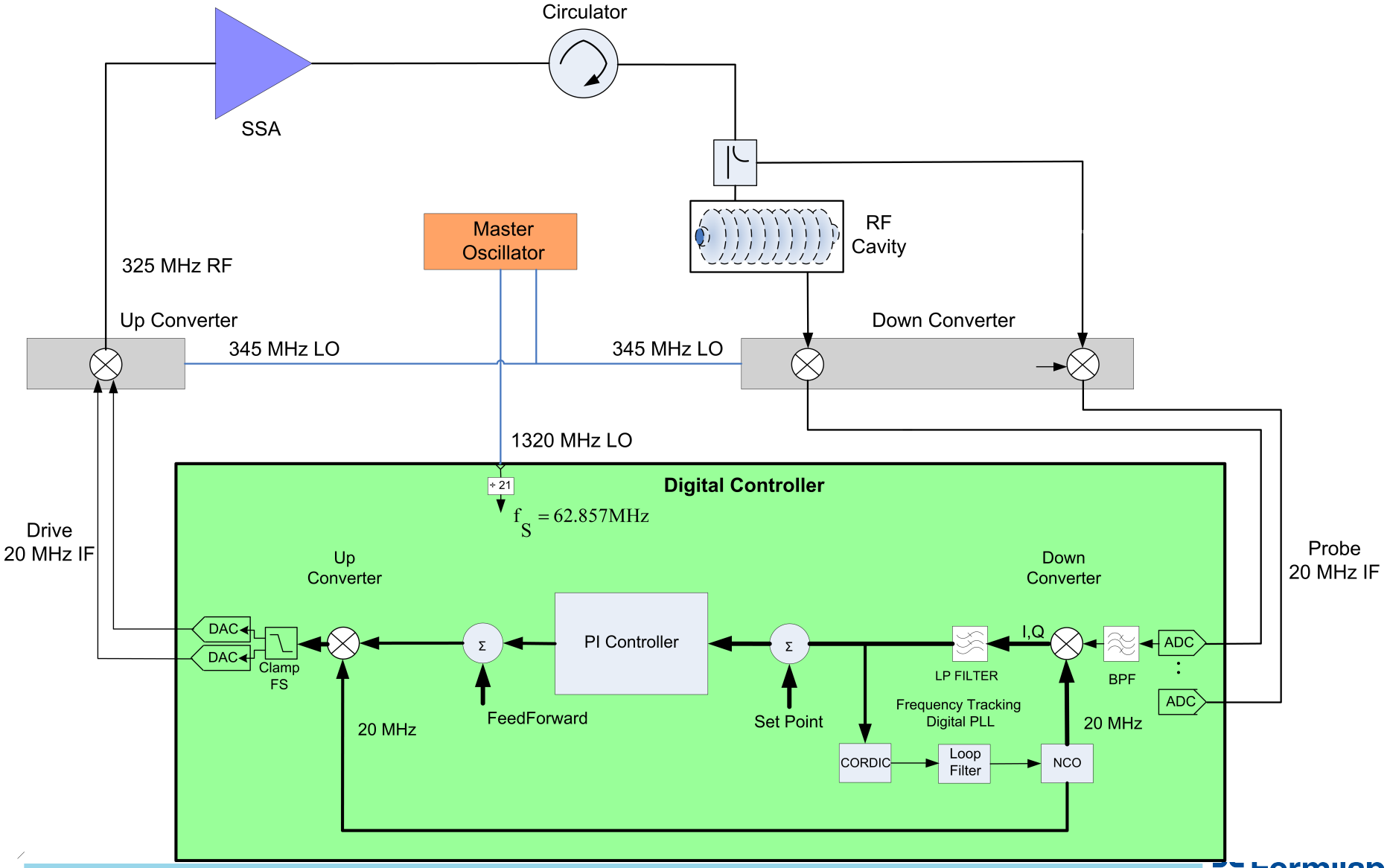




Fermilab

Simulation and Results

RF system control diagram



Baseband cavity and controller 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

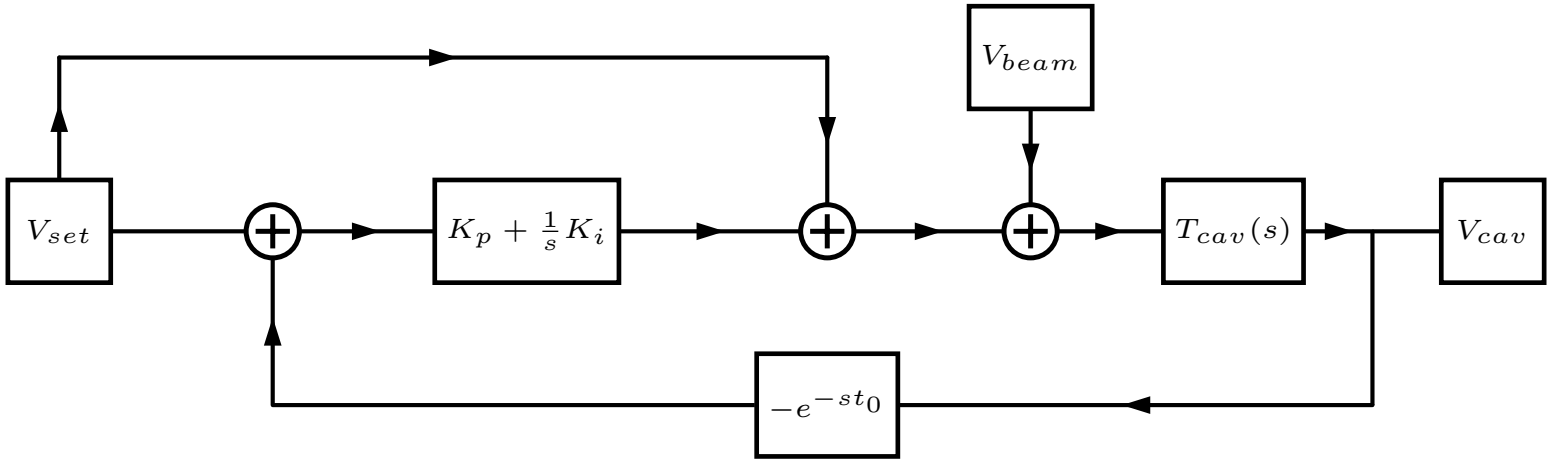
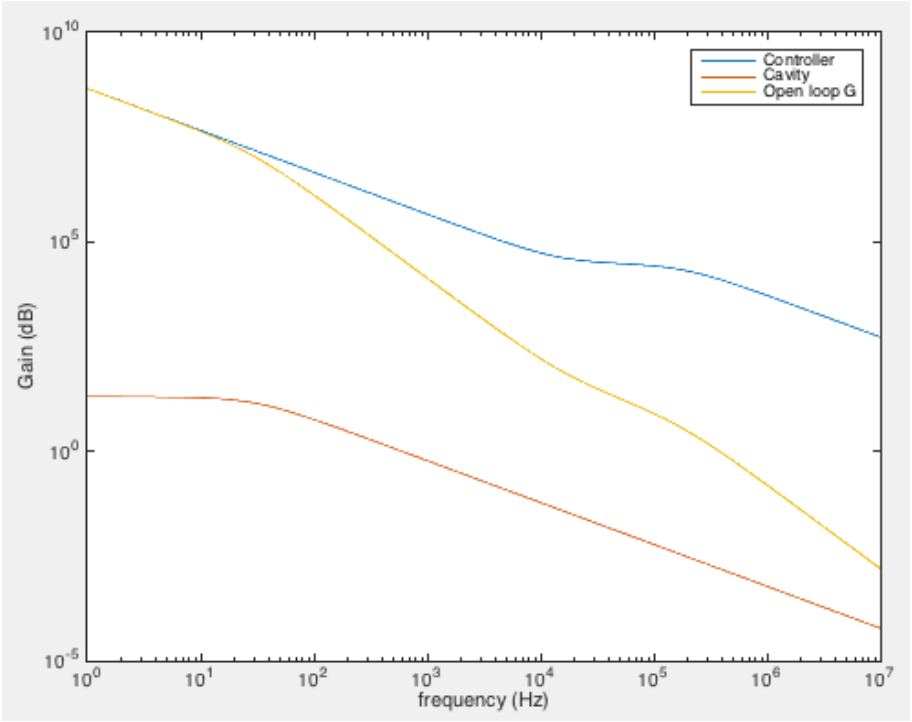


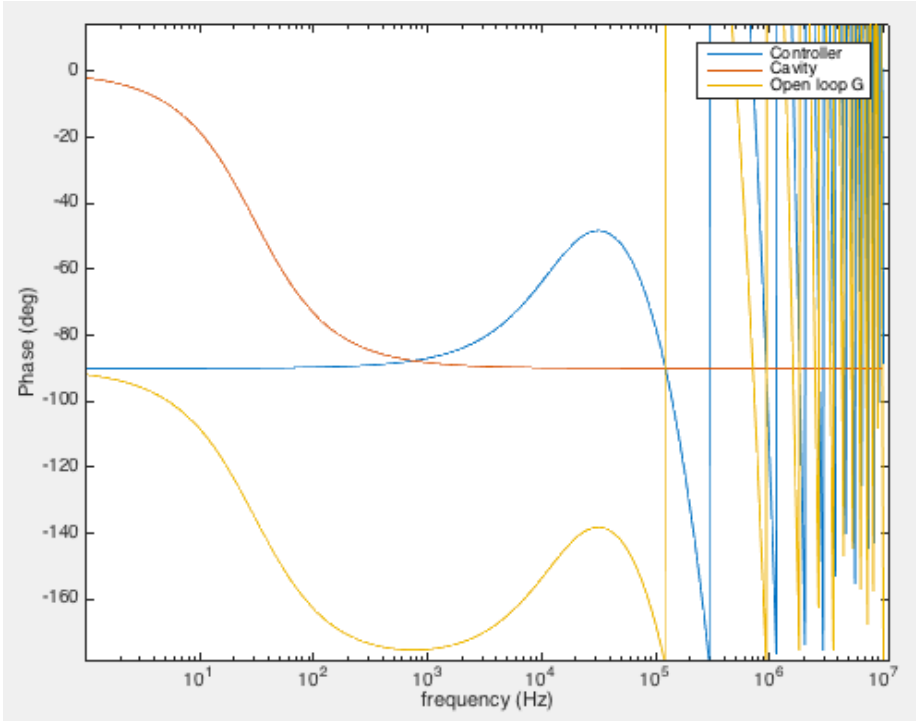
Figure: Baseband model of LLRF control system. Middle row (from left to right): Set-point, summing junction for feedback, PI controller, summing junction for feed-forward, summing junction for beam-loading, cavity transfer function, and cavity probe signal. Bottom row: group delay (negative for negative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

Open loop transfer function of cavity and controller

Magnitude



Phase



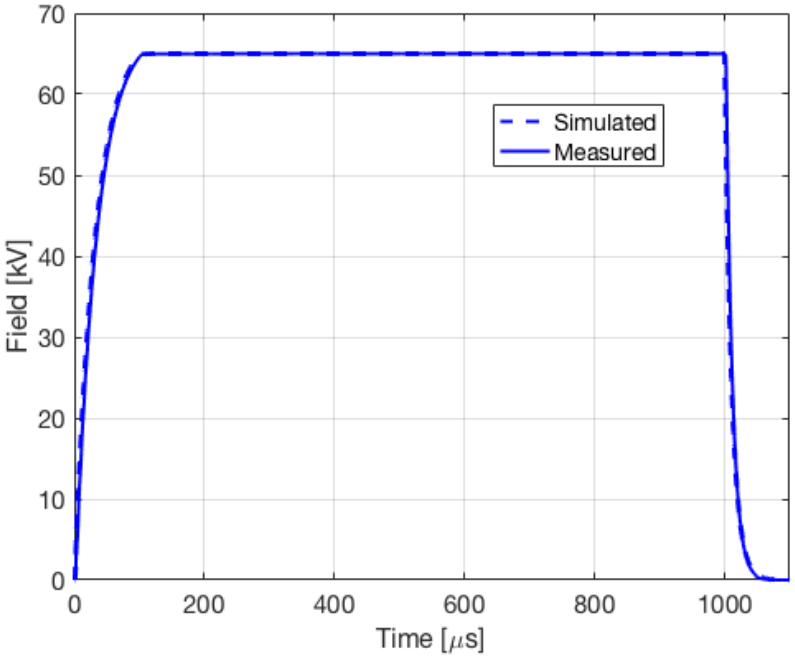
Max gain

Closed-loop bandwidth: ~50 kHz
Control system zero: 15 kHz
Proportional gain: 1500
Integral gain: 1.44e+08

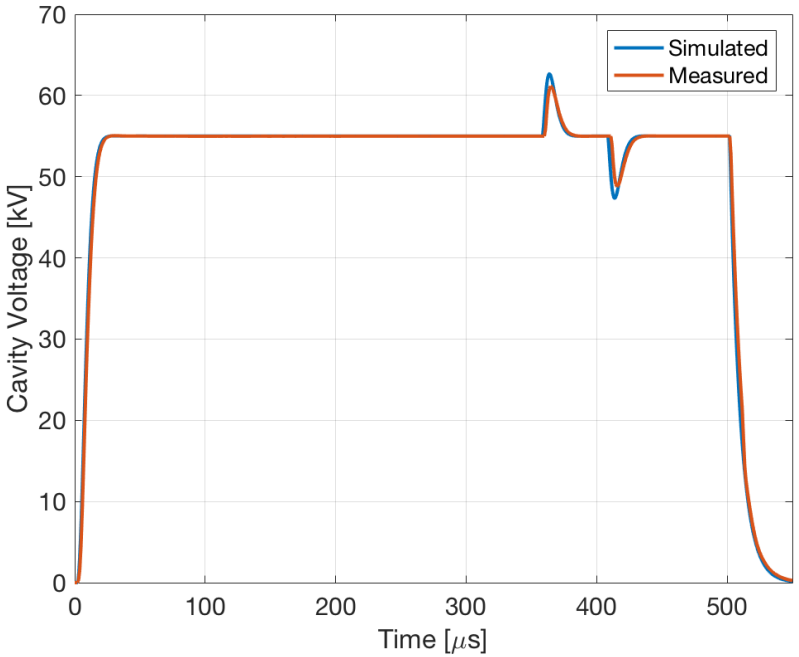
Nominal gain

Closed-loop bandwidth: ~25 kHz
Proportional gain: 750
Integral gain: 7e+07

RFQ and Buncher pulsed response



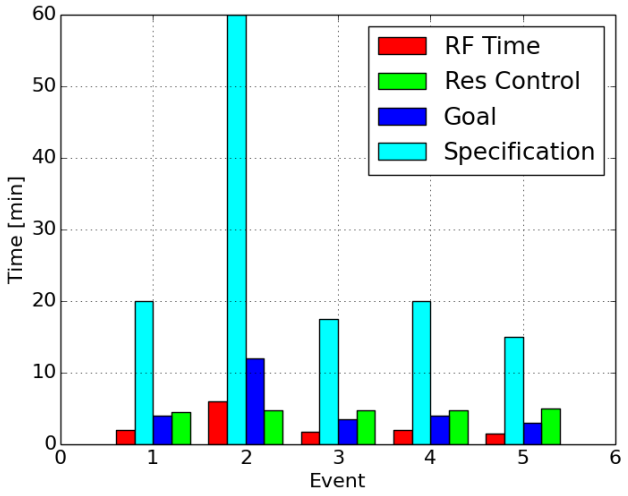
RFQ Pulse measured vs. simulated (Proportional and integral gains were 9.0 and 8.0e5 respectively)

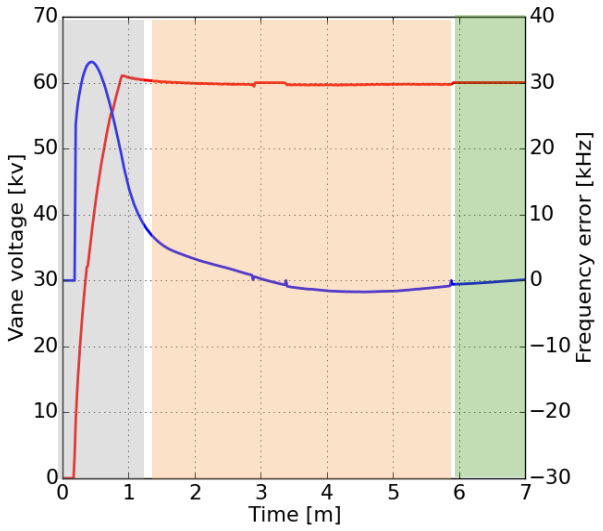


Buncher simulated vs. measured (kp 3.5, ki 6.0e5, Ql ~5000)

RFQ Resonance control status

- Currently meeting specification
  - Specification was to recover the RFQ in less than 10 times the RF recovery time
  - Goal of less than twice the RF recovery time
  - We anticipate meeting our goal requirement after the next round of improvements
- The controller interfaces with the water instrumentation, ACNET, and LLRF
- The controller framework is modular and can easily be improved or adapted to new systems
- Plans to improve performance will decrease the initial start time and decrease the trip recovery time





Vane voltage: Red
Frequency error: Blue
Grey: RFQ ramp, resonance control is idle, LLRF is in SEL
Orange: Resonance control bringing RFQ to frequency, LLRF is in SEL
Green: RFQ is in GDR and LLRF feedback is active

Conclusions

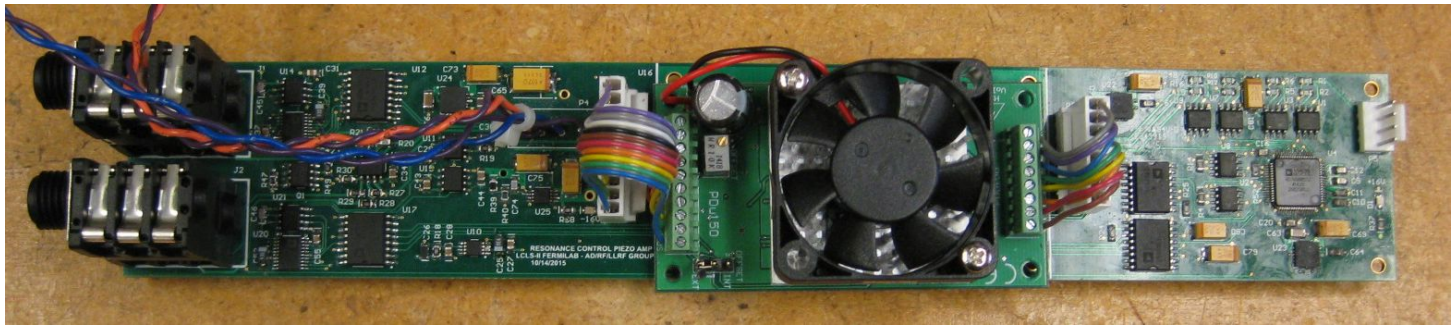
- PIP2IT LLRF is operational with the RFQ and first buncher and are on schedule for the next stages.
- IIFC joint designs are are making good progress
- PIP-II LLRF detailed level requirements are still being refined with simulation and PIP2-IT experience

Thank you for your attention!

Backup slides

Piezo Resonance Control Requirements

- Minimize microphonics to <10 Hz
- 1 Hz or better resolution
- +- 1kHz tuning range
- 2 drive amplifiers for 2 piezo stack groups per cavity
  - (1 module per cavity)
  - 4 drive modules per chassis



Piezo Amplifier – PDu150

Load (uF)	Voltage Range 50 V	100 V	150 V
0.01	64000	32000	21000
0.03	21000	11000	7100
0.1	6400	3200	2100
0.3	2100	1100	710
1	640	320	210
3	210	110	71
10	64	32	21
30	21	11	7

Table 1. Power bandwidth (in Hz) with a capacitive load

Load Capacitance	Signal 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

Table 2. Small signal bandwidth (-3 dB)

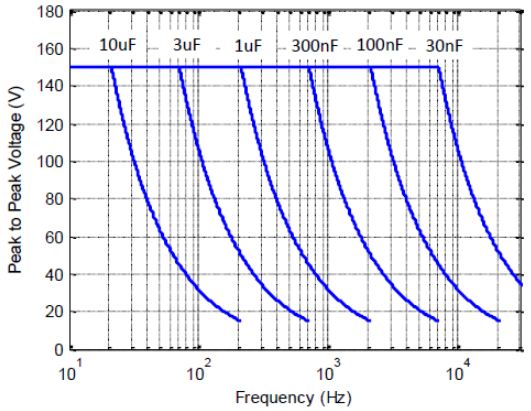


Figure 3. Power Bandwidth (150 Vp-p)

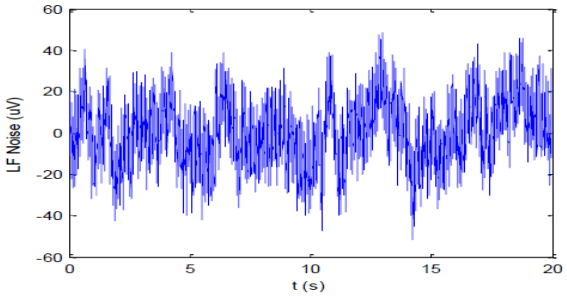


Figure 5. Low frequency output noise (0.03 Hz to 10 Hz)

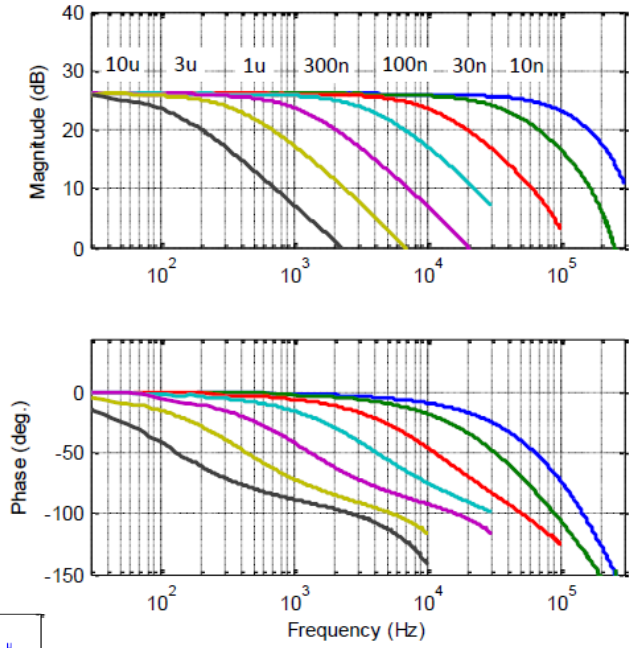
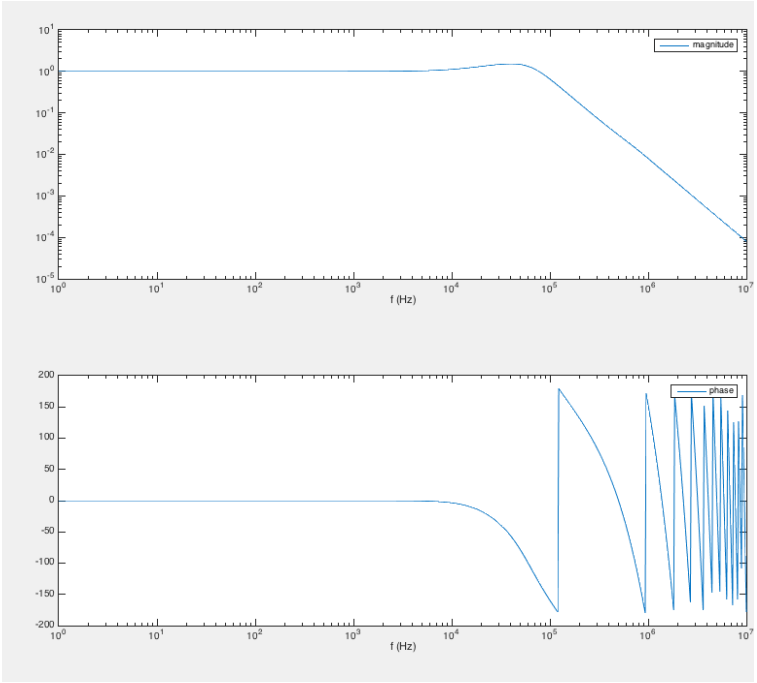


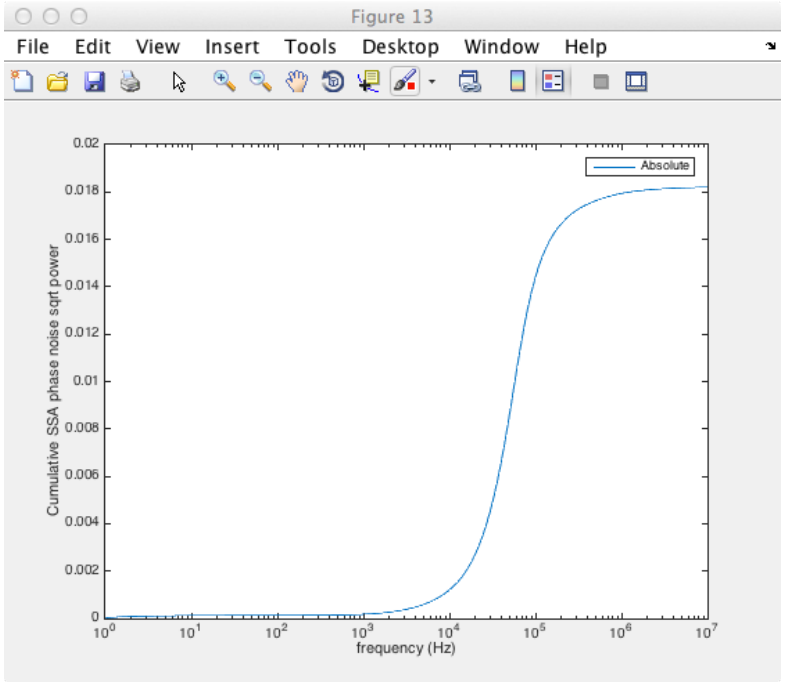
Figure 4. Small signal frequency response

Total phase noise to SSA from controller and oscillator

Closed loop response



Cumulative SSA phase noise voltage

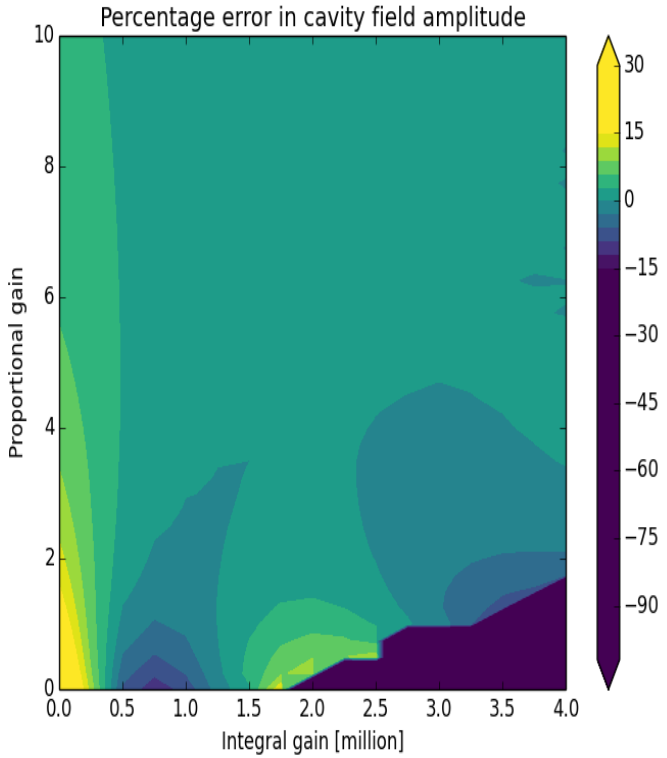


Careful attention to noise terms will allow high controller gains

- Cavity: 0.00078° rms
- SSA: 1.04°
- SSA from ADC noise 0.96°

Code developed for LCLS-II
Larry Doolittle LBNL and FNAL

Feedback gain studies

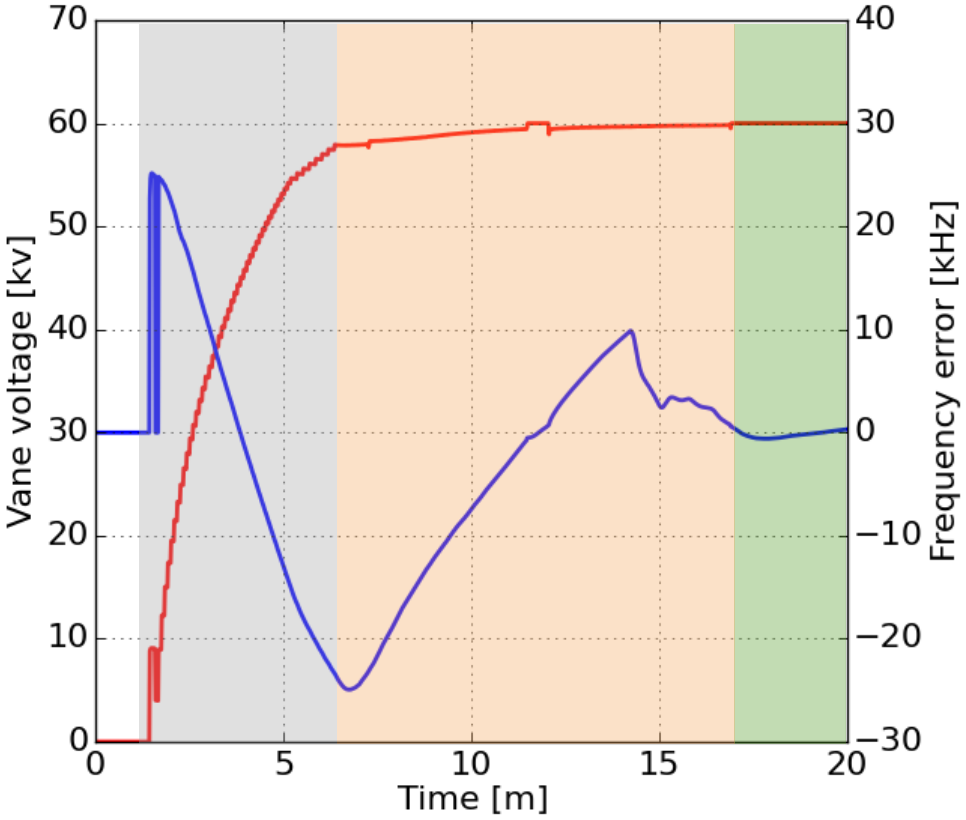


- Percentage error in the cavity field amplitude at 20 microseconds after a disturbance
- The disturbance was 10% of full scale
- For cases with large integral gain and low proportional gain, the feedback loop is unstable

5 min ramp. Mostly automated (operator tuning at 14 minutes to speed things up a little)

Testing faster start, not fully automated. Kink in resonance frequency at 14 minutes was due to operator tuning not automatic tuning.

Vane voltage: Red
Frequency error: Blue
Grey: RFQ ramp, resonance control is idle, LLRF is in SEL
Orange: Resonance control bringing RFQ to frequency, LLRF is in SEL
Green: RFQ is in GDR and LLRF feedback is active

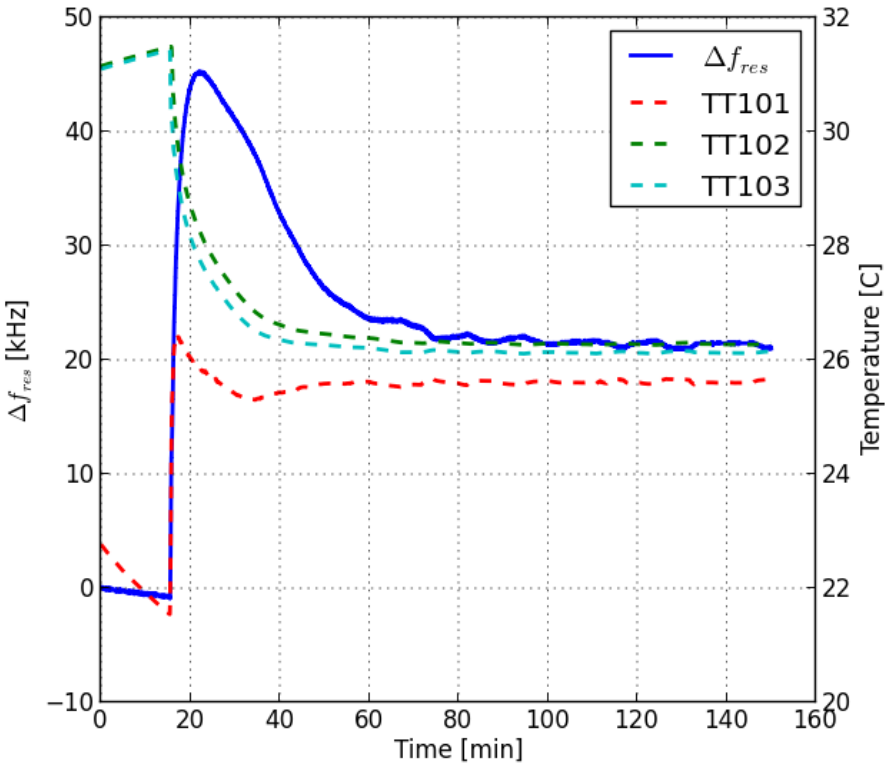


RFQ vane system step response

	initial	transient	steady state
Time	0	7.2 min	115.4 min
Δf_{res}	0	46.13 kHz	21.15 kHz
TT_{101}	22.280 ^{o}C	25.796 ^{o}C	25.649 ^{o}C
TT_{102}	31.489 ^{o}C	28.126 ^{o}C	26.141 ^{o}C
TT_{103}	30.941 ^{o}C	27.639 ^{o}C	26.284 ^{o}C

flow path	time delay [s]
$TT_{101} \rightarrow TT_{103}$	1.0
$TT_{103} \rightarrow TT_{102}$	17.0

- Transient response of the RFQ resonant frequency due to change in the vane flow control valve. Prior to changing the flow valve, the intermediate skid was cooled to approximately 25C. The control valve was stepped from 0% open to 50% open.



Feedback requirements and analysis

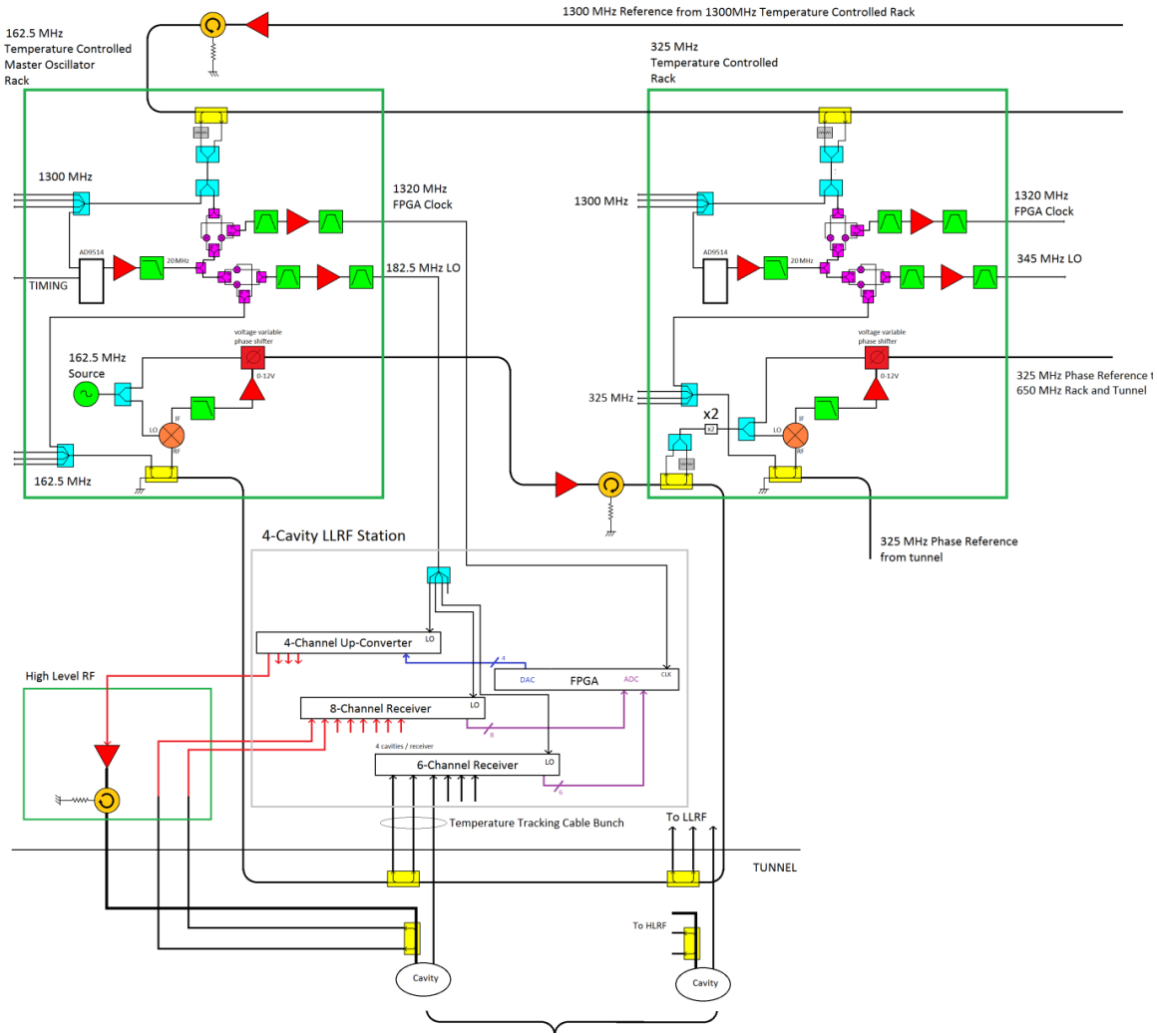
- Expecting large disturbances from LFD, want fast response from beam loading transient
  - get 15 dB from feedforward beamloading compensation
- Approach - find highest stable loop gain and determine system noise requirements
- Determine best gain settings from operational experience and needs of beam-based feedback
  - It is easy to turn down the gain on a well designed system, impossible to turn up gain on a poorly designed one
- Assume a low noise oscillator
  - Wenzel VHF ULN 100 MHz 13.7 dBm
  - % http://www.wenzel.com/model/vhf-uln/
- System loop delay of 2.1 μsec
- Cavity bandwidth 30 Hz

Details of First 162.5 MHz RF Section

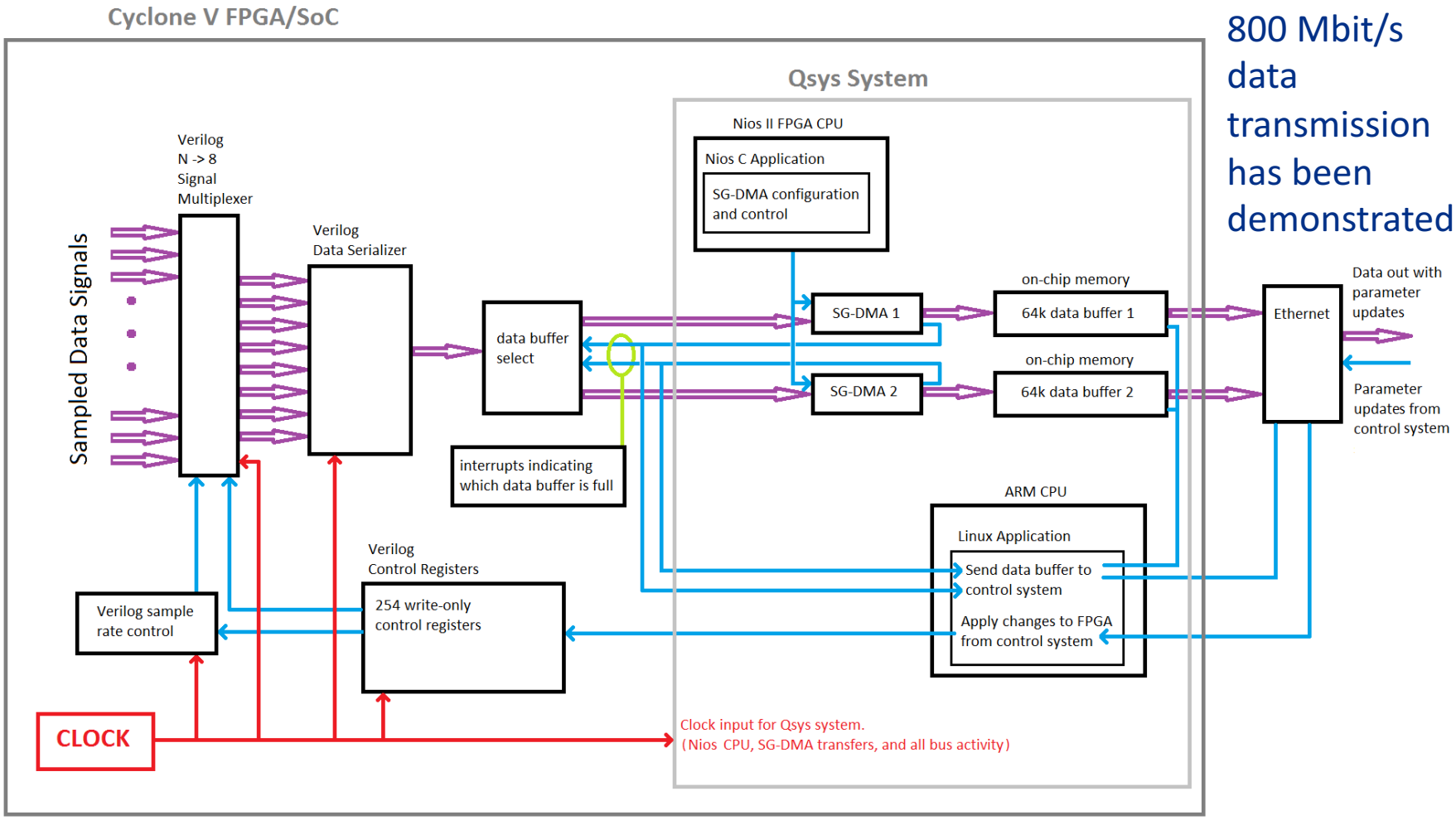
Phase stability across harmonics (400 fs)

Temperature controlled racks and component plates

We have this experience and see a path forward



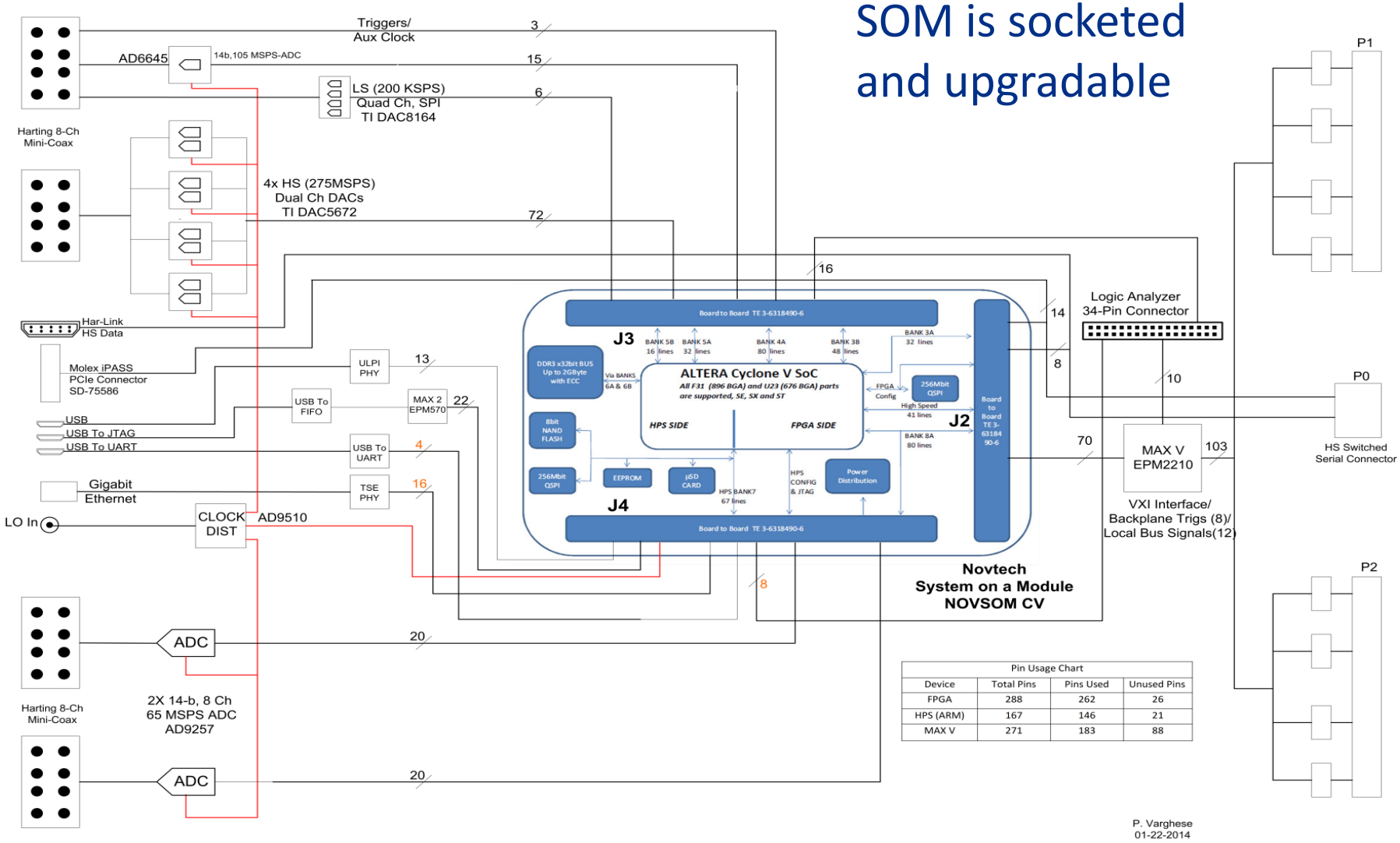
SOC Data Acquisition Software / Firmware Model



800 Mbit/s data transmission has been demonstrated

System on Module Multi-cavity Field Controller (SOM-MFC)

SOM is socketed and upgradable



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

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01-22-2014