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Low Level RF Control System

Brian Chase for the LLRF team

PIP-II Machine Advisory Committee Meeting

15-17 March 2016

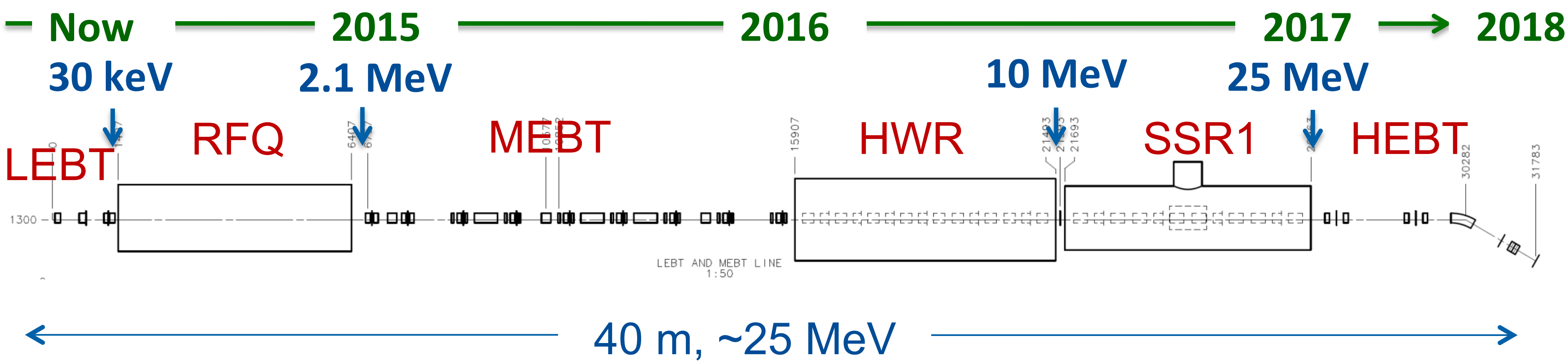
Outline

- System overview
  - LLRF
  - Reference line
  - 4 cavity Station
  - Controller cards
  - Piezo amp for resonance control
- RFQ commissioning results
- Requirements and design approach
  - 0.01°, 0.01% rms beam stability
  - 0.1°, 0.1% rms field stability per cavity
  - Large non deterministic detuning errors
- Collaborations
  - India
  - Colorado State University
- Current system development
  - Master Oscillator and Reference line
  - Controller module
    - System on module

Team

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

PXIE Low Level RF Group Involvement



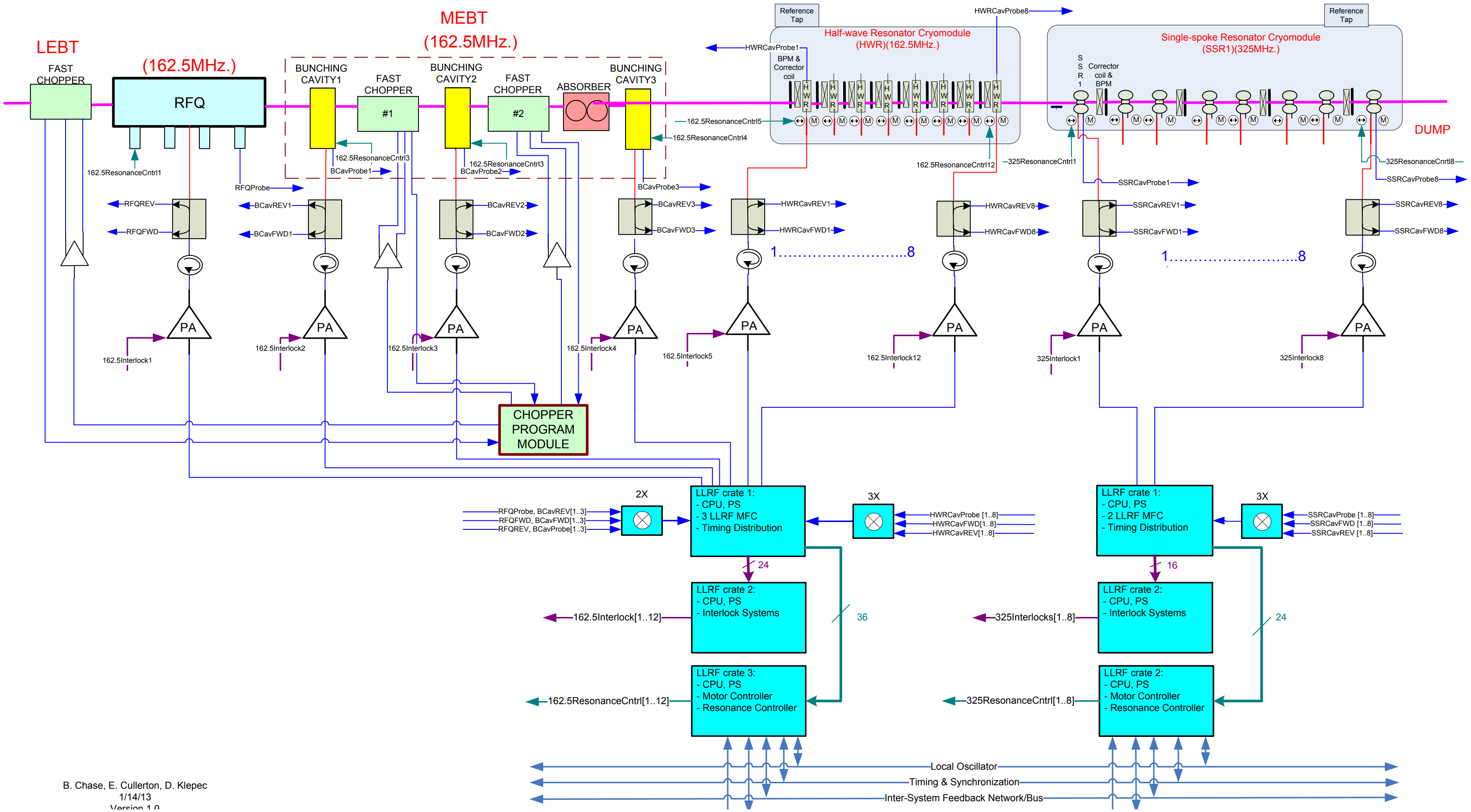
PXIE will address the address/measure the following:

- LEBT pre-chopping
- Vacuum management in the LEBT/RFQ region
- Validation of chopper performance
- Bunch extinction
- MEBT beam absorber
- MEBT vacuum management
- Operation of HWR in close proximity to 10 kW absorber
- Operation of SSR with beam, including resonance control and LFD compensation in pulsed operations
- Emittance preservation and beam halo formation through the front end

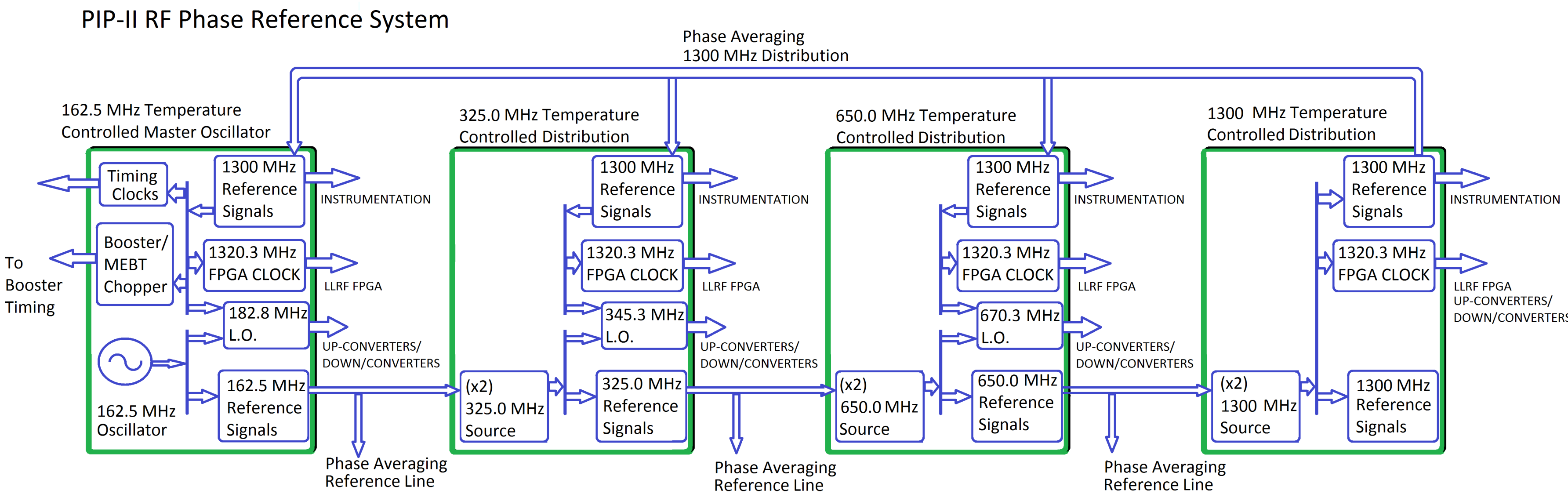
LLRF Systems needed to meet R&D Goals

- 325 MHz Horizontal test stand
  - Support for CW and pulsed mode operation
  - Operational
- 650 MHz Horizontal test stand
  - Support for CW and pulsed mode operation
  - Supplied by India Q3FY16
- PXIE
  - Master Oscillator and Phase Reference distribution line
    - 162.5 MHz & 325 MHz (Operational with synthesizer)
  - RFQ – 162.5 MHz (Q4FY15)
    - 2 RF amplifier system (In system test/ resonance testing)
  - Buncher - 3 cavities - 162.5 MHz (FY15) (Ready for 1st buncher)
  - Half Wave Resonators - 8 cavities @162.5 MHz (FY17)
  - SSR1 - 8 cavities @ 325 MHz (FY17)
  - Kicker waveform generator

PIXIE RF Stations Diagram



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



Multi-frequency Phase References and Local Oscillators
We are building up the first sections for PXIE

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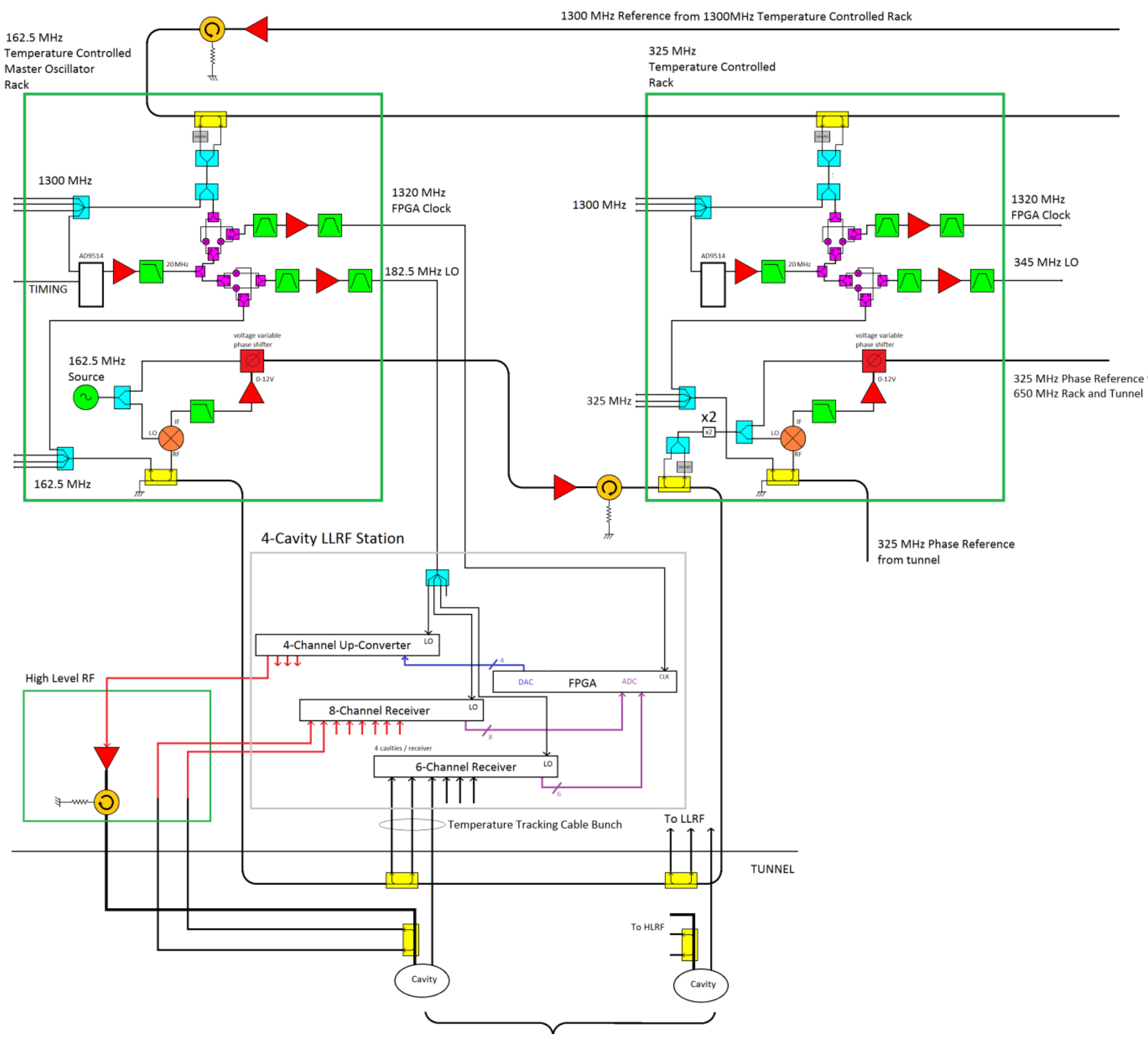
Details of First 162.5 MHz RF Section

Phase stability across harmonics (400 fs)

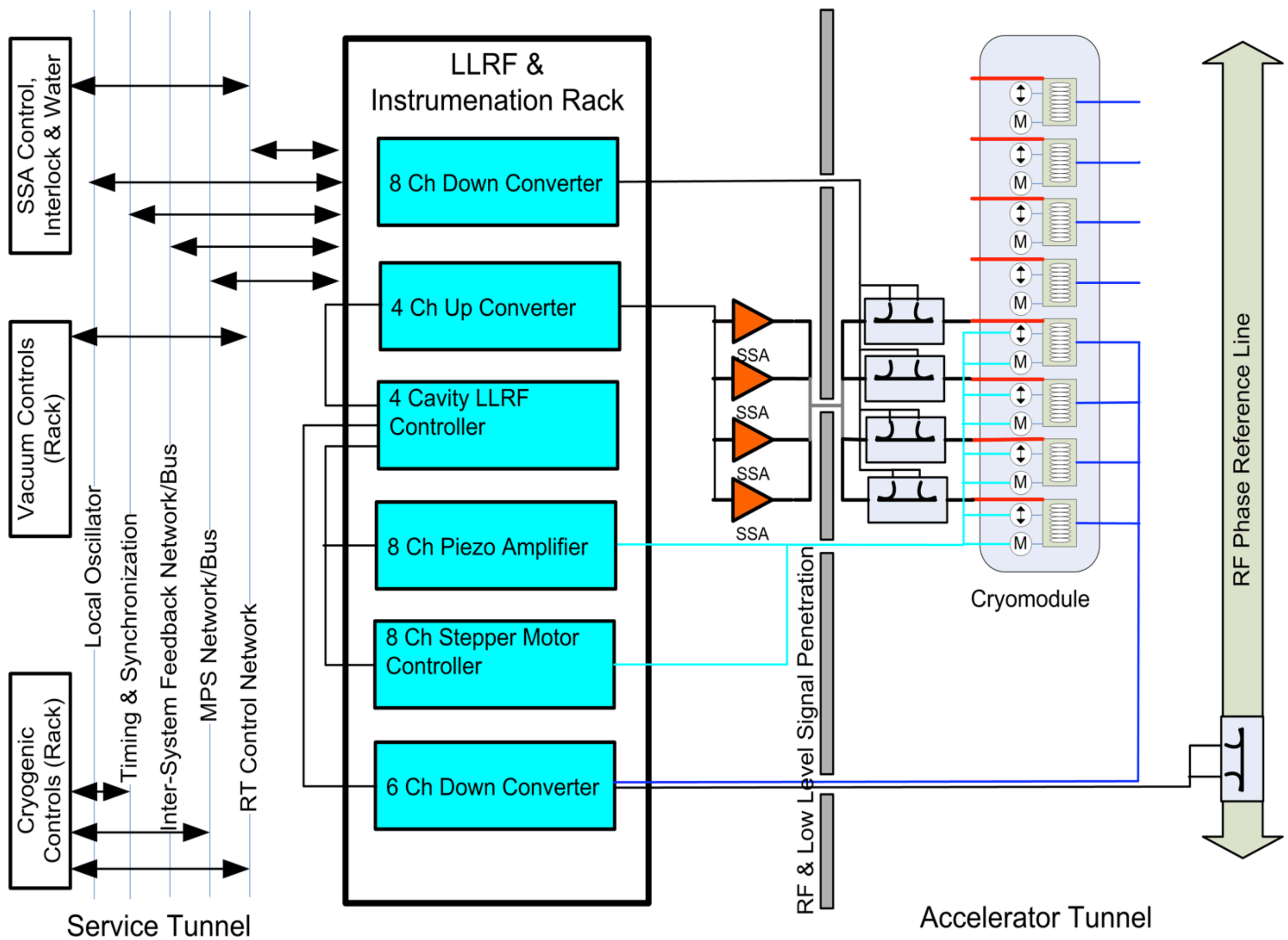
Temperature controlled racks and component plates

We have this experience and see a path forward

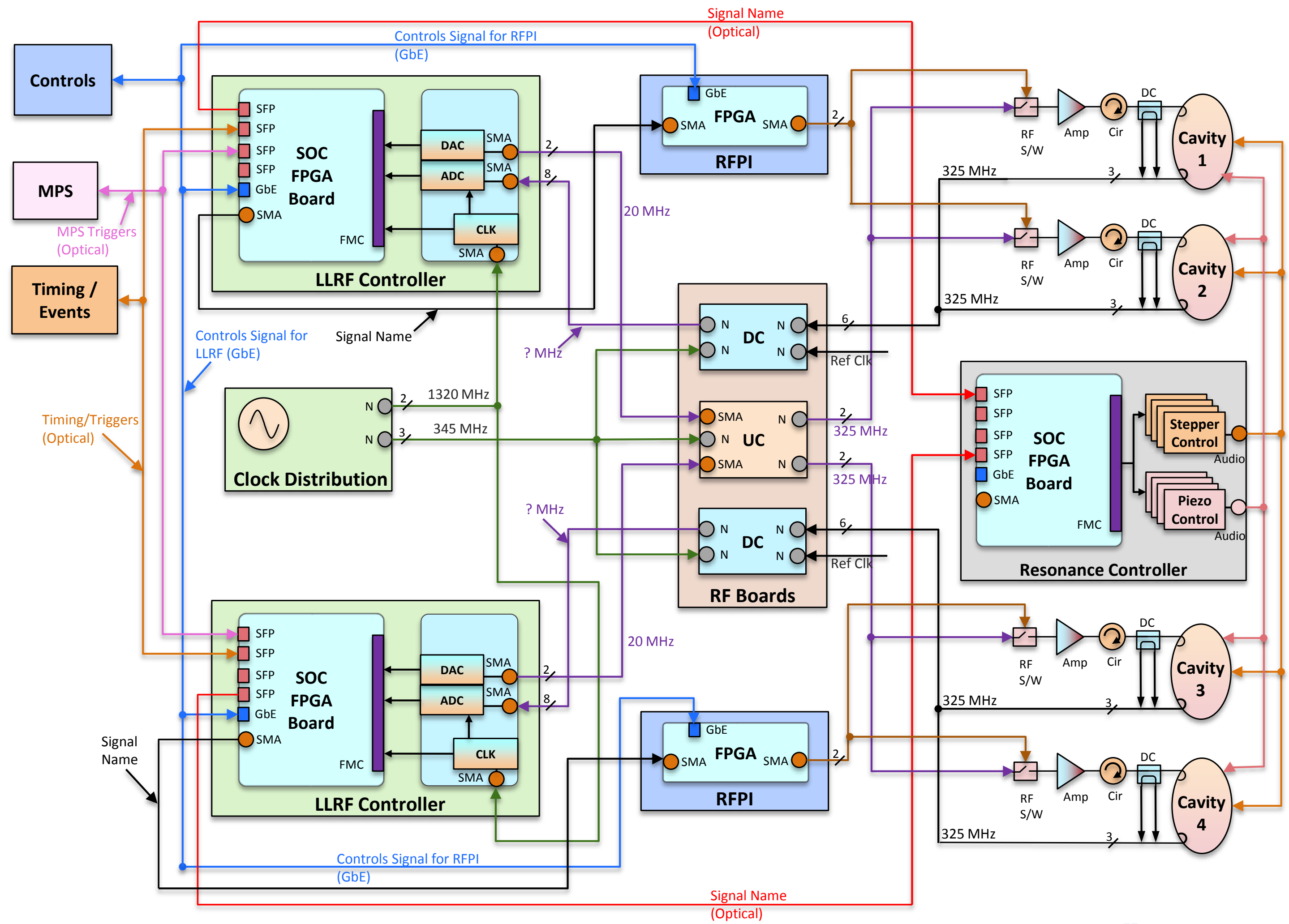


PIP-II LLRF 4 Cavity LLRF Rack Layout

Down converters for
PXIE are done
Controller, PZT amp,
stepper motor controller,
Up converter
in design stage



Basic LLRF Station Diagram for 4 cavities



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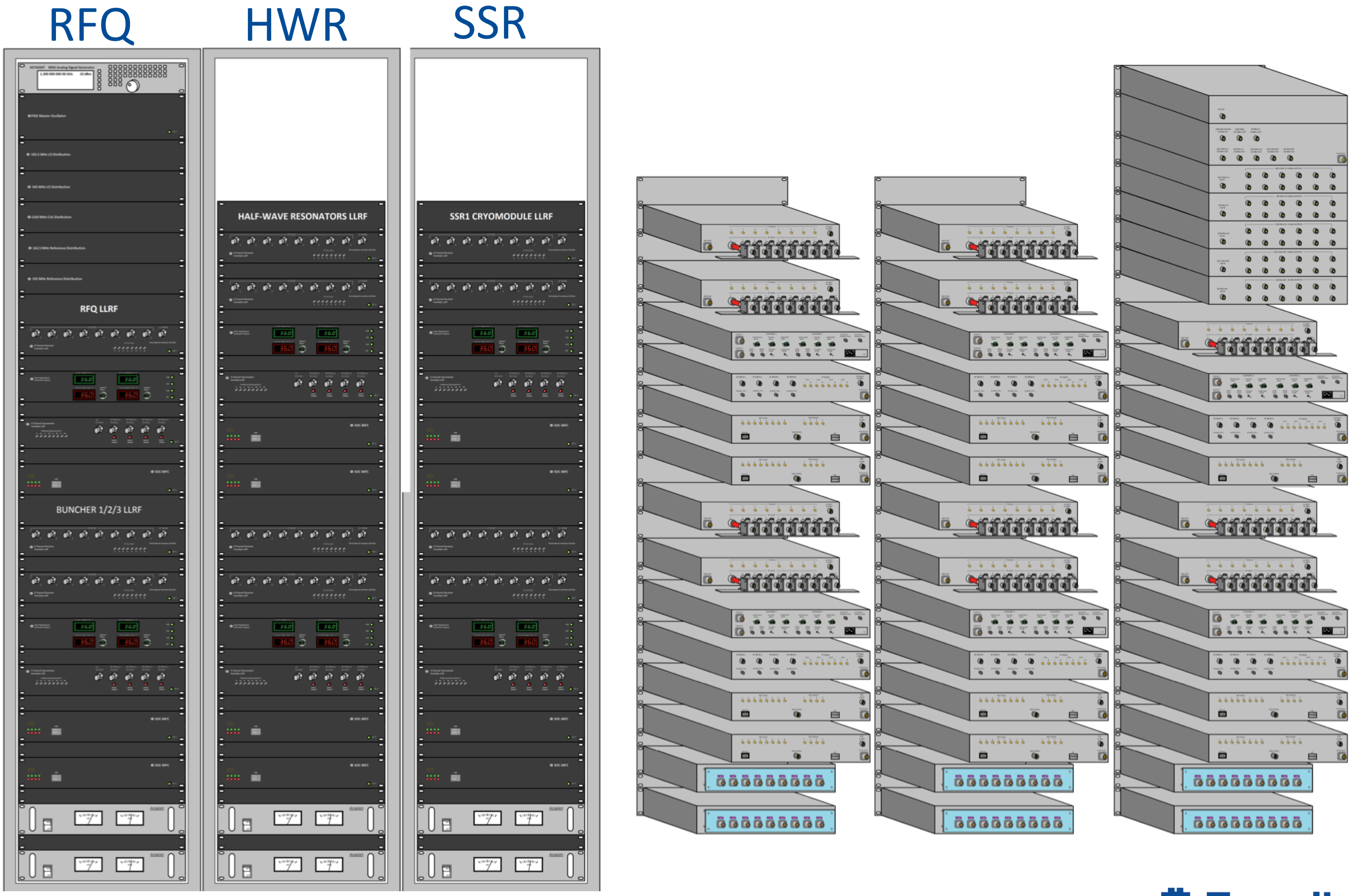
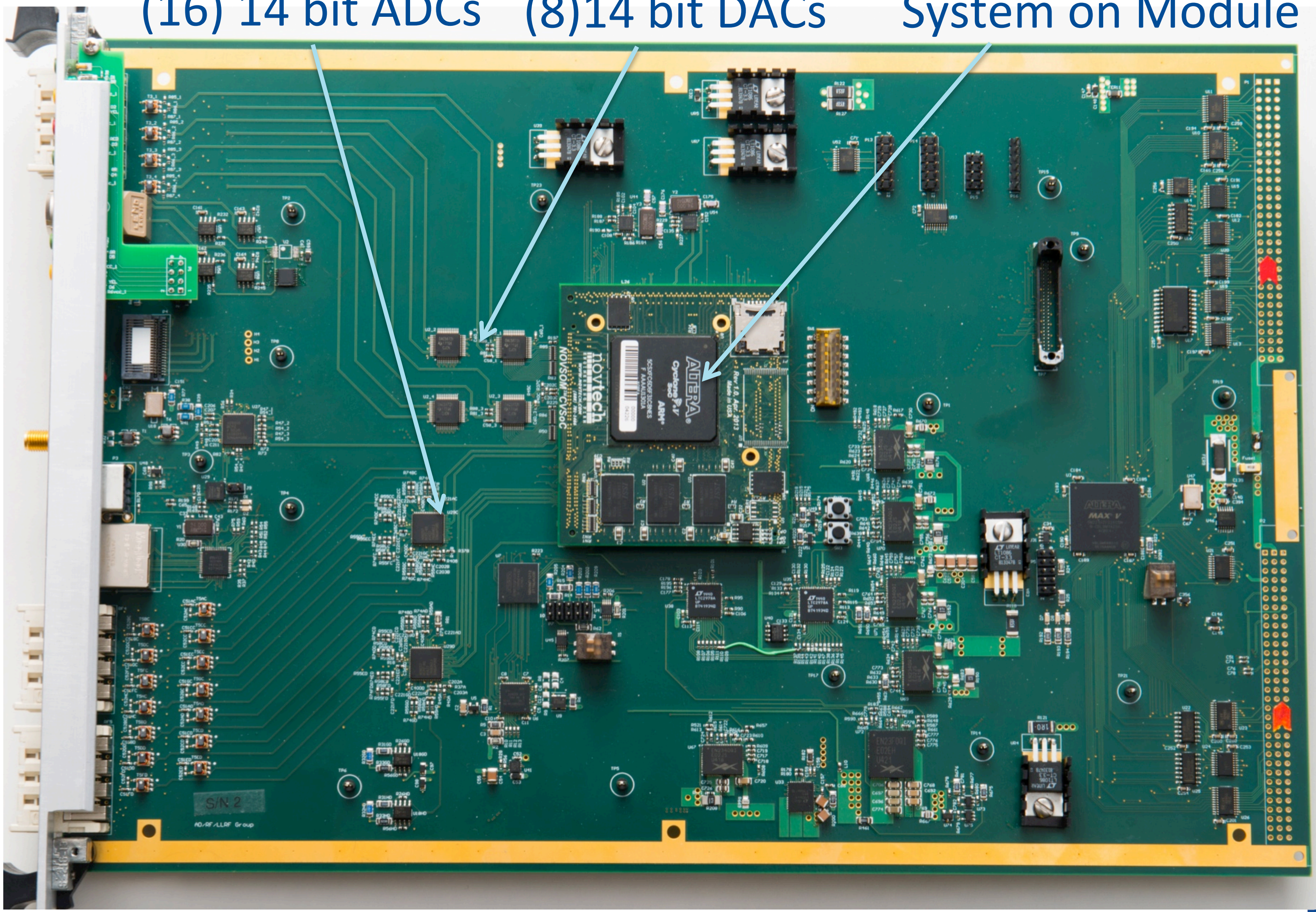
PXIE LLRF rack layout - front and rear view



System on Chip Multi-channel Field Controller

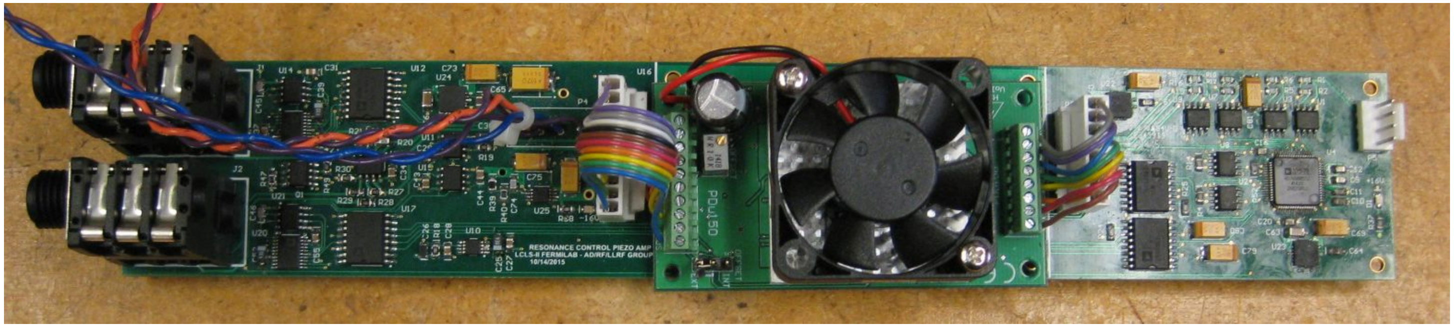


Dual core Arm processor with FPGA may eliminate the need for a backplane and CPU card

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

Each amp drives 2.2uF piezo loads

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

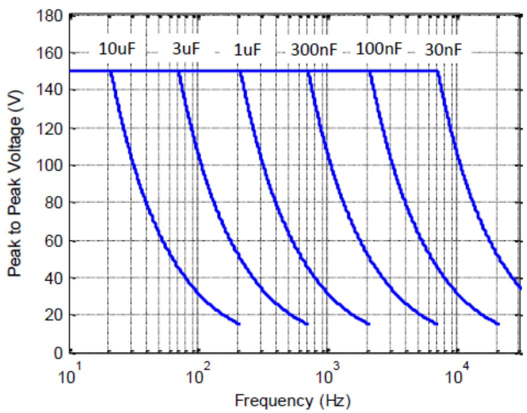


Figure 3. Power Bandwidth (150 Vp-p)

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)

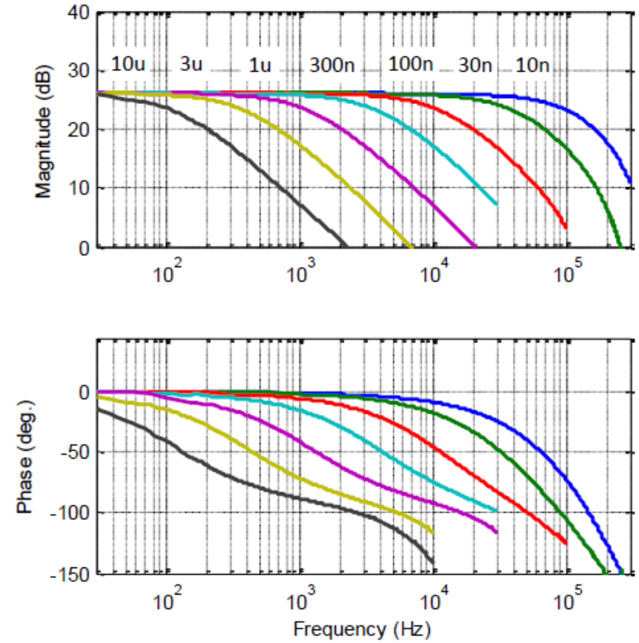
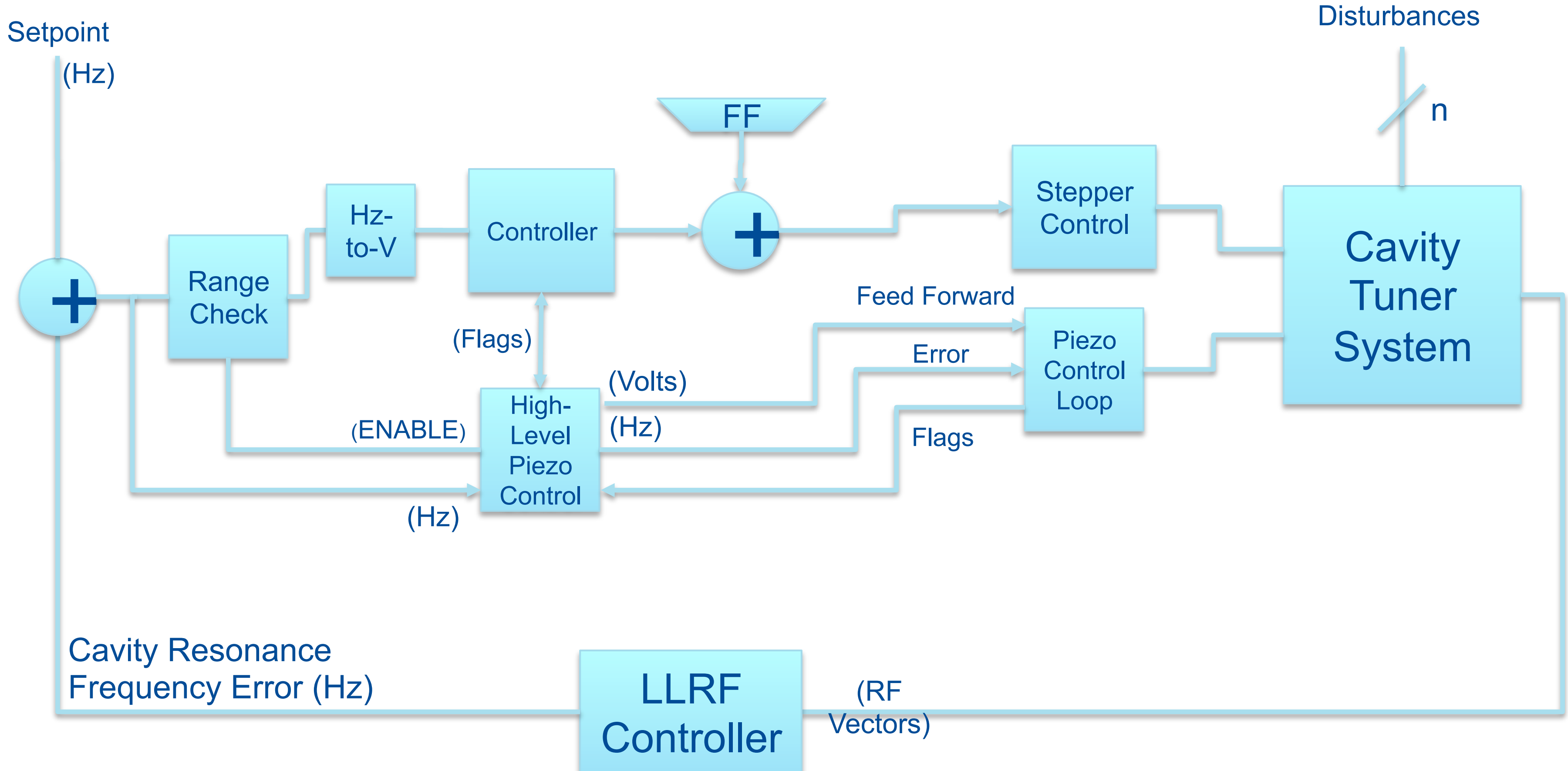


Figure 4. Small signal frequency response

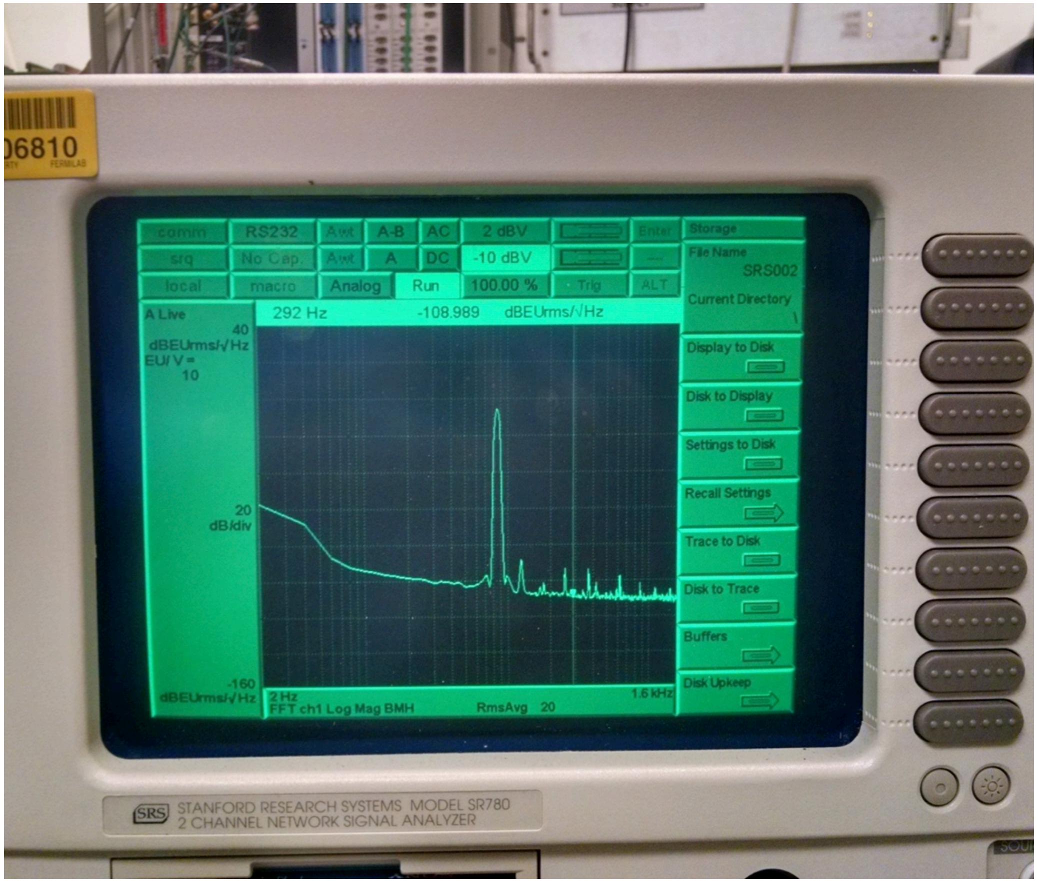
Resonance Control Loop



Piezo Amplifier single tone and noise performance

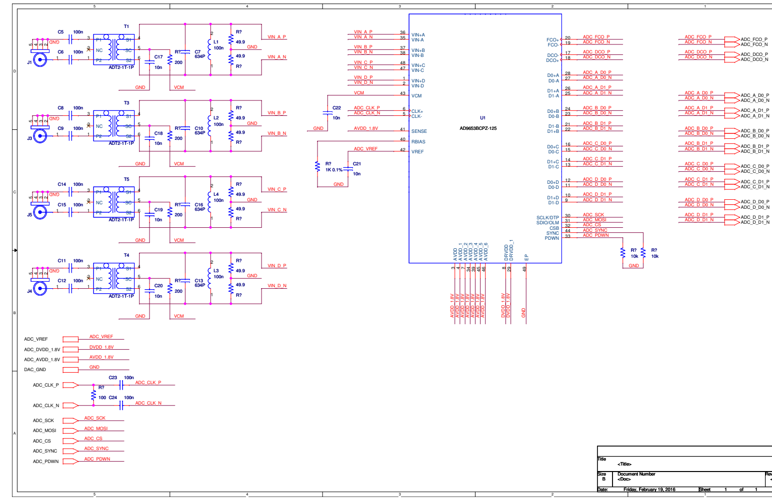
Low distortion with 86 Hz sine wave

-109 dBV/√Hz @ 292 Hz



IIFC LLRF Status

Cards with schematics
- ADC/DAC, FPGA, Up-converter
- Down-converter, Piezo amplifier



Layouts are coming soon

Two engineers are working here with us for a two year period

	Major Milestones	Quantity	Institution	Fermilab-SPM	DAE - SPC	CY16 – CY19
94	**LLRF System**		BARC	Chase	Joshi	
95	Initial Design Specification of LLRF System					Delay due to access to engineering
96	Prototype of the LLRF System for Horizontal Test Stand being developed by DAE laboratories for Fermilab	1				Delay in initial design spec, plus more realistic schedule
97	Development of Prototype LLRF System for the Horizontal Test Stand being developed by DAE laboratories for DAE laboratories and Fermilab.	2				
98	Development of a new LLRF System for the SSR1 Cryomodule being developed by Fermilab	1				Minimize delay by procuring all hardware simultaneously
99	Development of a new LLRF System for the CMTF being developed by DAE laboratories for Fermilab	1				
100						

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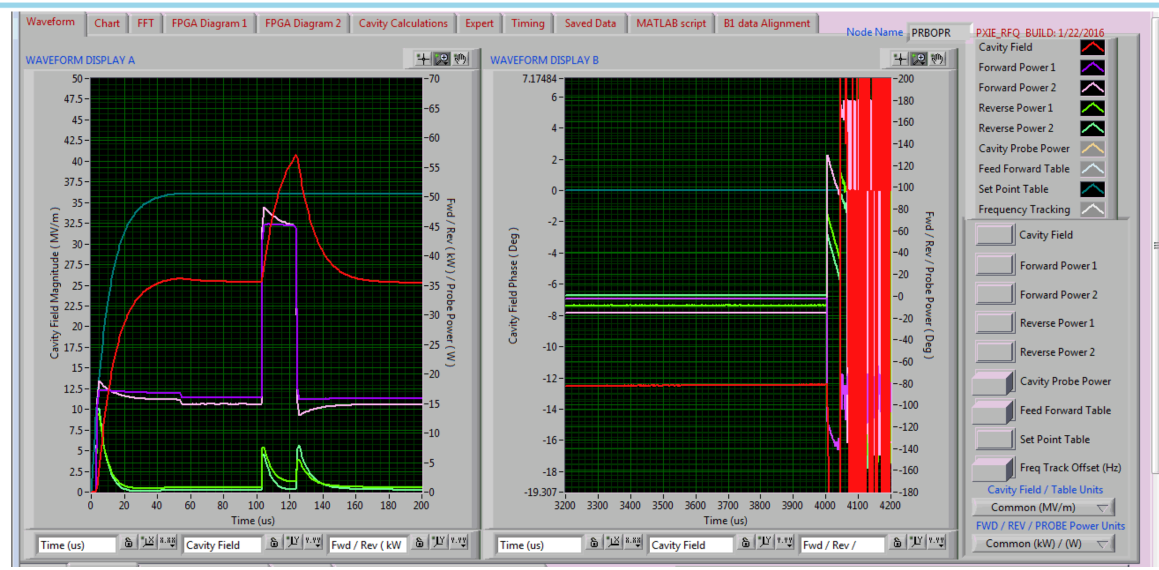
RFQ disturbance response

Open loop response to a 20 μsec full scale disturbance



Closed loop

Q_l = 6900

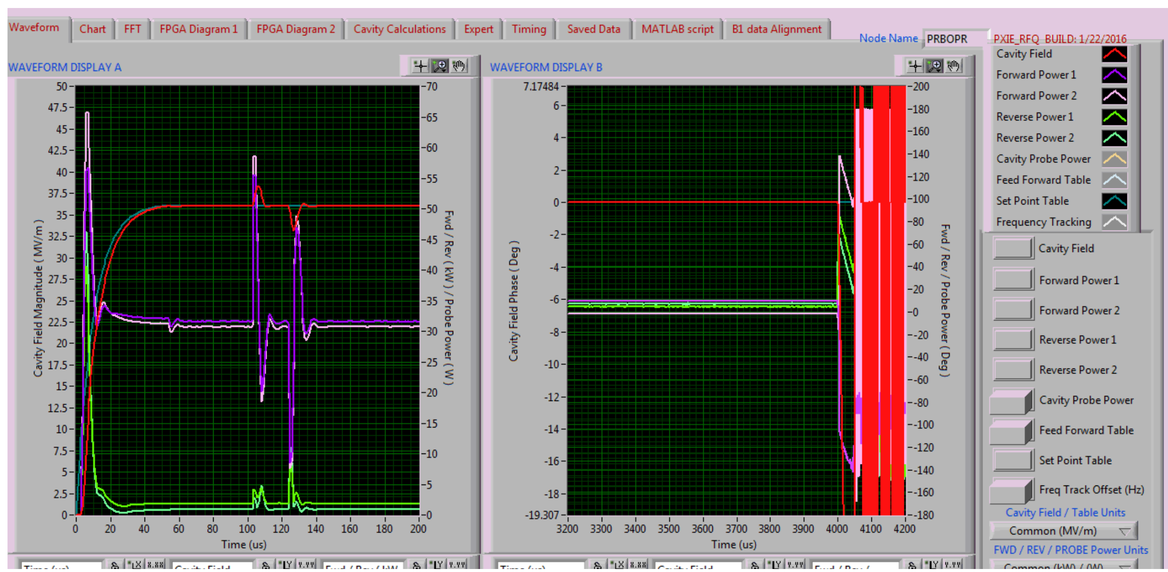
Kp=6

Ki=3.5e6

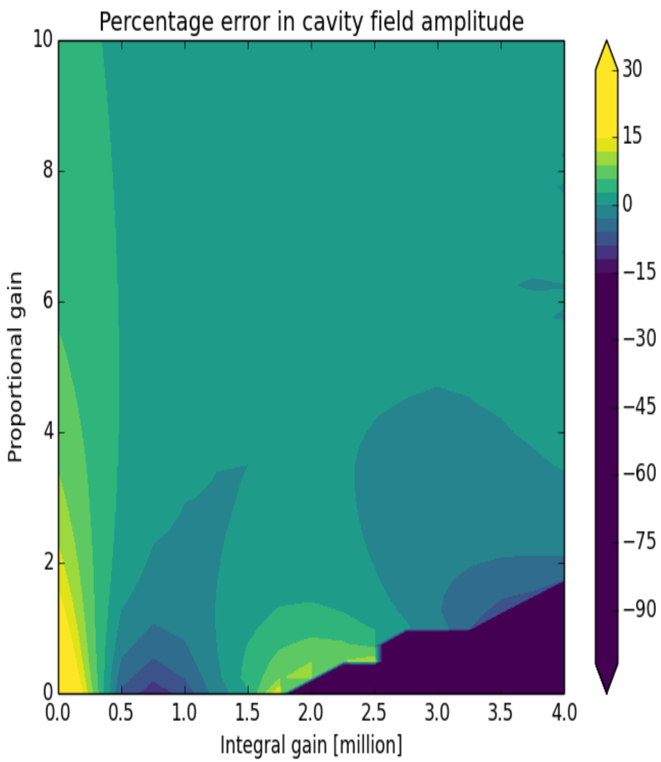
settling time~10 μsec

In loop noise measurement

0.008% rms, < 0.002° rms



Feedback gain studies



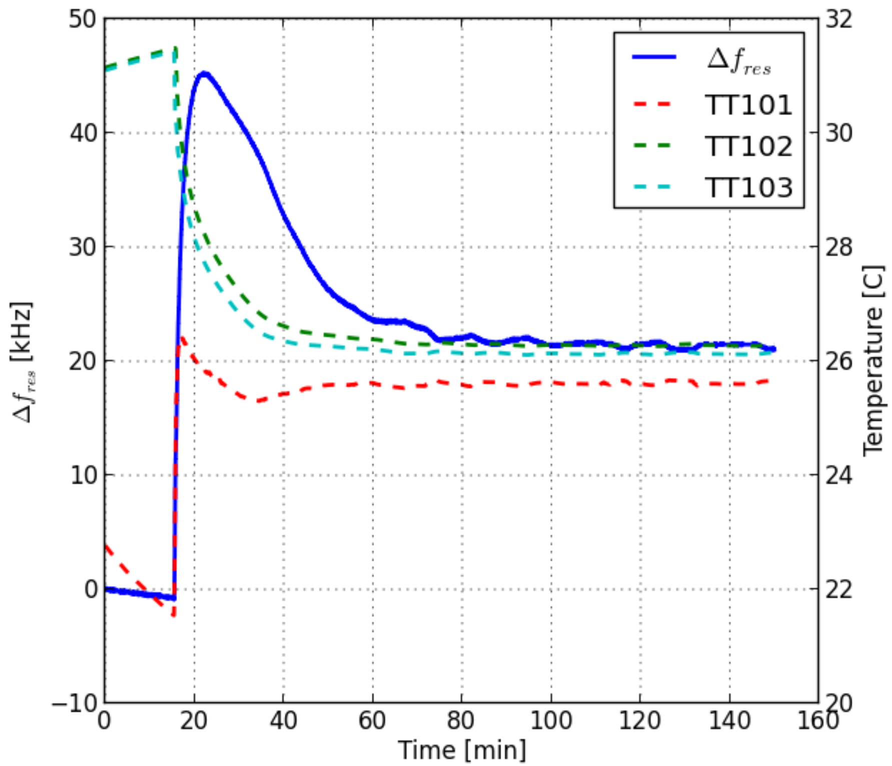
- Percentage error in the cavity field amplitude at 20 microseconds after a disturbance
- The disturbance was 10% of full scale
- For cases with large integral gain and low proportional gain, the feedback loop is unstable

RFQ resonance control vane system step response

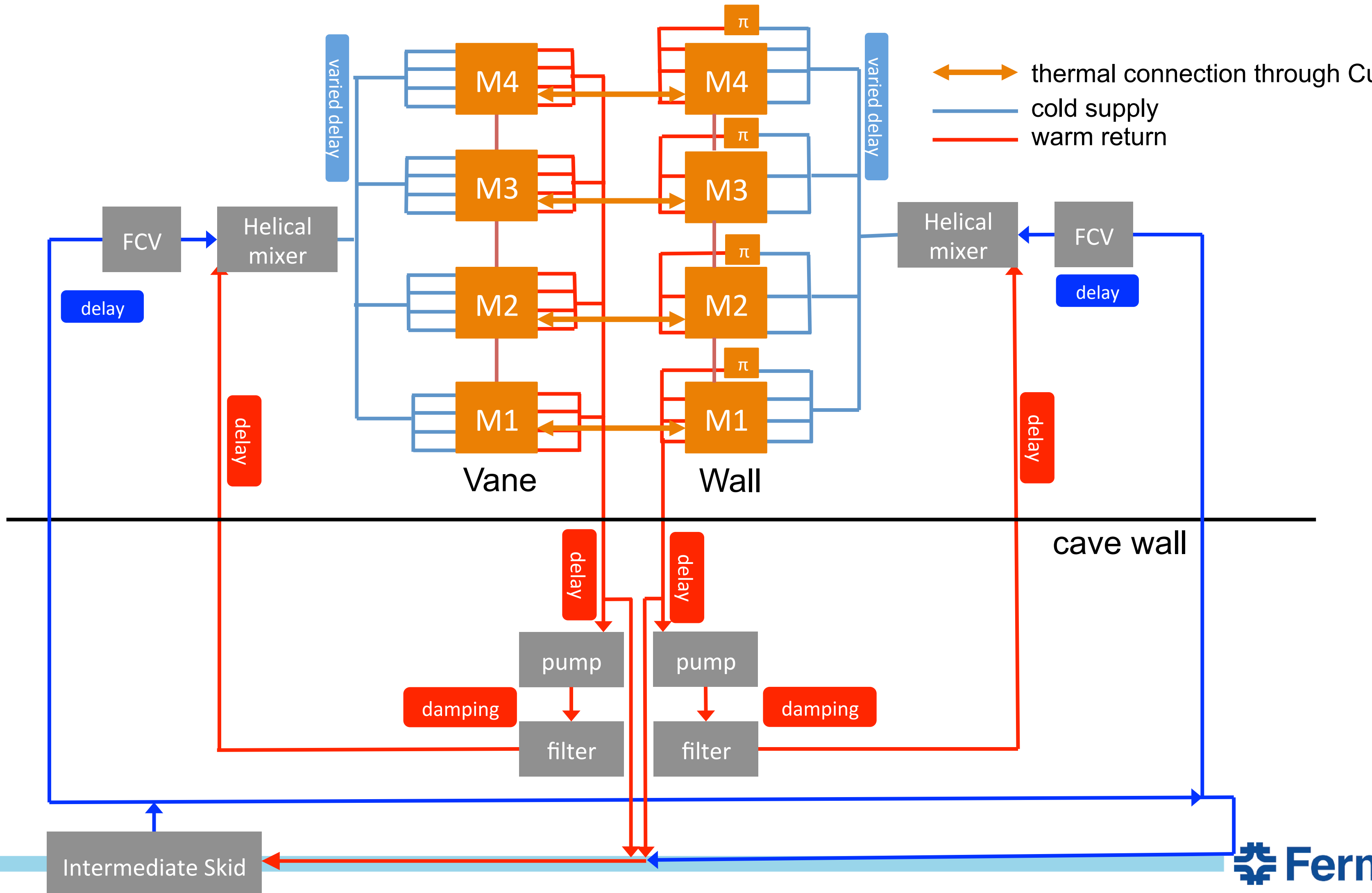
	initial	transient	steady state
Time	0	7.2 min	115.4 min
Δf_{res}	0	46.13 kHz	21.15 kHz
TT_{101}	22.280 ^{o}C	25.796 ^{o}C	25.649 ^{o}C
TT_{102}	31.489 ^{o}C	28.126 ^{o}C	26.141 ^{o}C
TT_{103}	30.941 ^{o}C	27.639 ^{o}C	26.284 ^{o}C

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.



RFQ Water system overview



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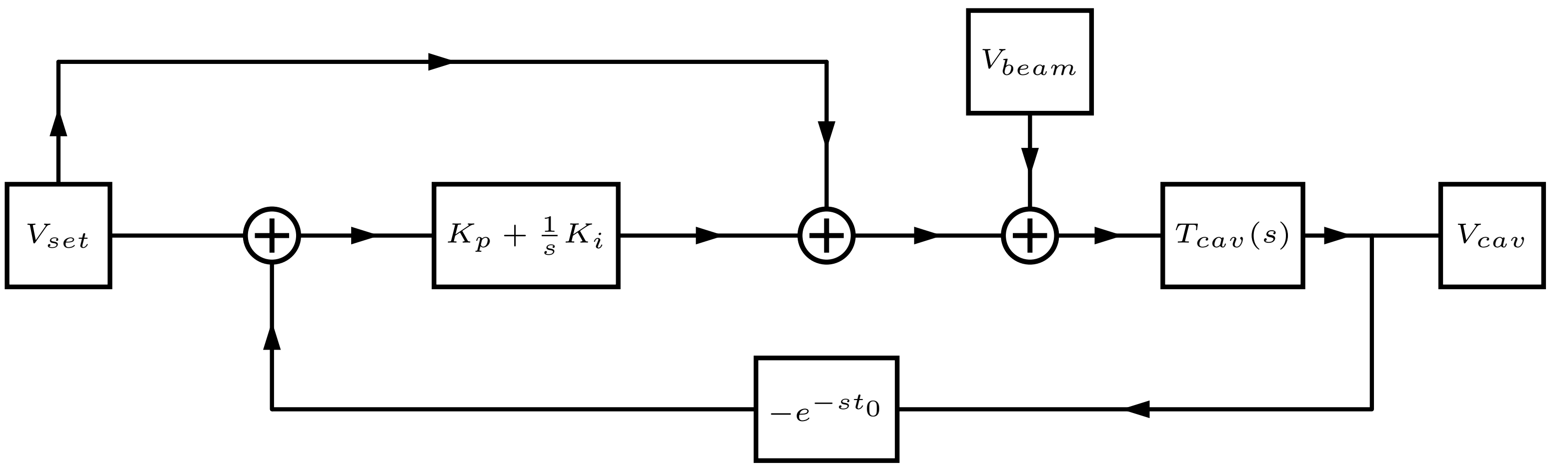
Feedback modeling

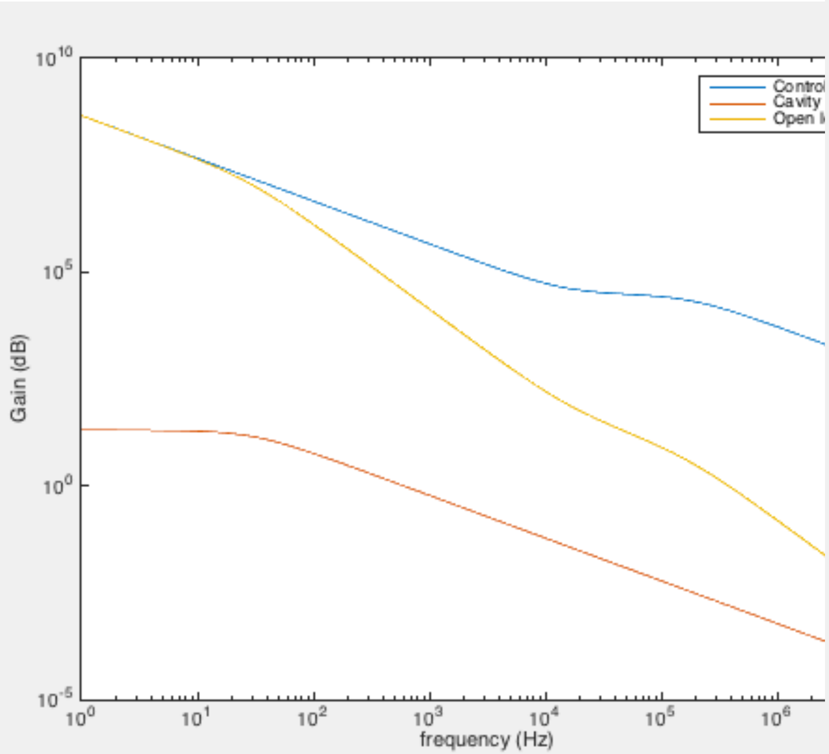
- Expecting large disturbances from LFD, want fast response from beam loading transient
  - get 15 dB from feedforward beamloading compensation
- Approach - find highest stable loop gain and determine system noise requirements
- Determine best gain settings from operational experience and needs of beam-based 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

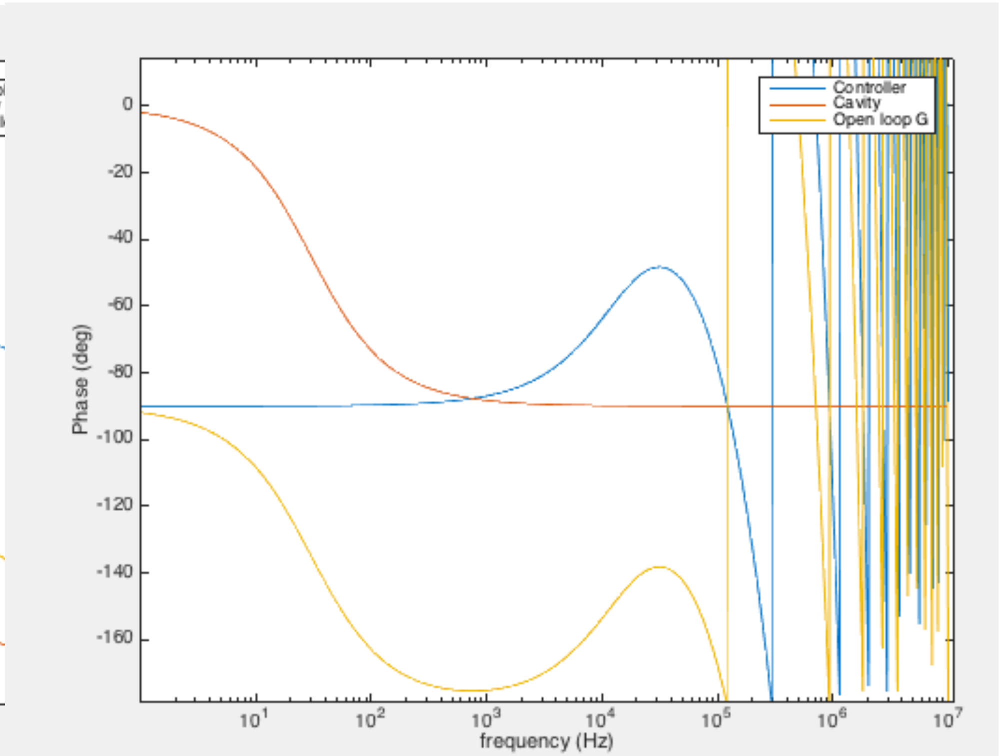


Simulation of open loop transfer function of cavity and controller

Magnitude



Phase

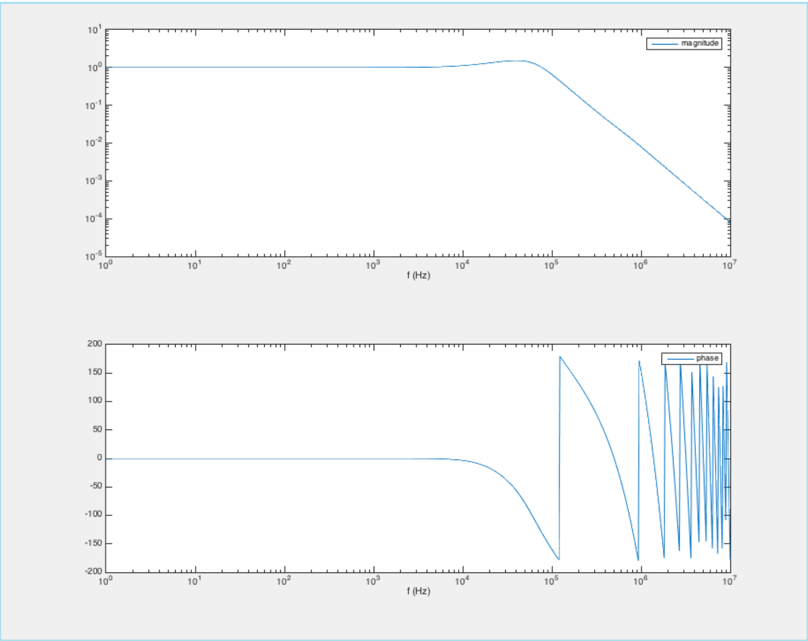


Closed-loop bandwidth: ~50 kHz
Control system zero: 15 kHz
Proportional gain: 1500
Integral gain: 1.44e+08

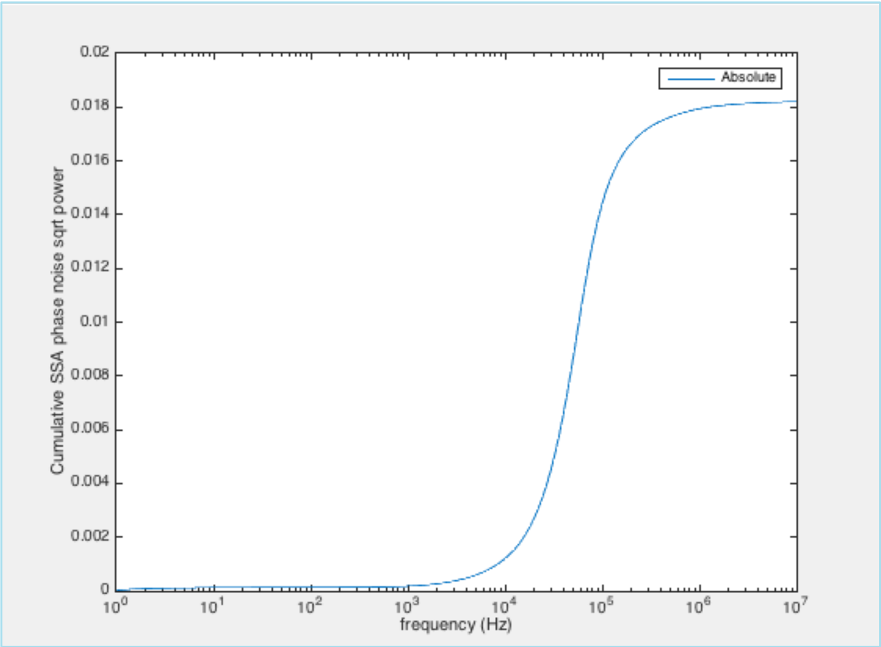
Code developed for LCLS-II
Larry Doolittle LBNL and FNAL

Total phase noise to SSA from controller and oscillator sources

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: 0.96°

Conclusions

- The LLRF Group is commissioning and developing systems for PXIE
  - Development of a next generation system controller card
  - Development of the multi-frequency reference
  - RFQ resonance control
  - MEBT/kicker waveform generator
  - Simulation tools
- Collaboration with India to deliver next generation systems for test stands and LLRF control for the 120 cavities of PIP-II

Thank you for your attention!

Primary Technical Risks

- Resonance 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
- Development of the LEBT/MEBT Chopper Program Module
  - Wideband beam-based learning algorithm
- 10^{-3} regulation of amplitude and phase in pulsed mode with high Q cavities
- 10^{-4} regulation with beam based feedback

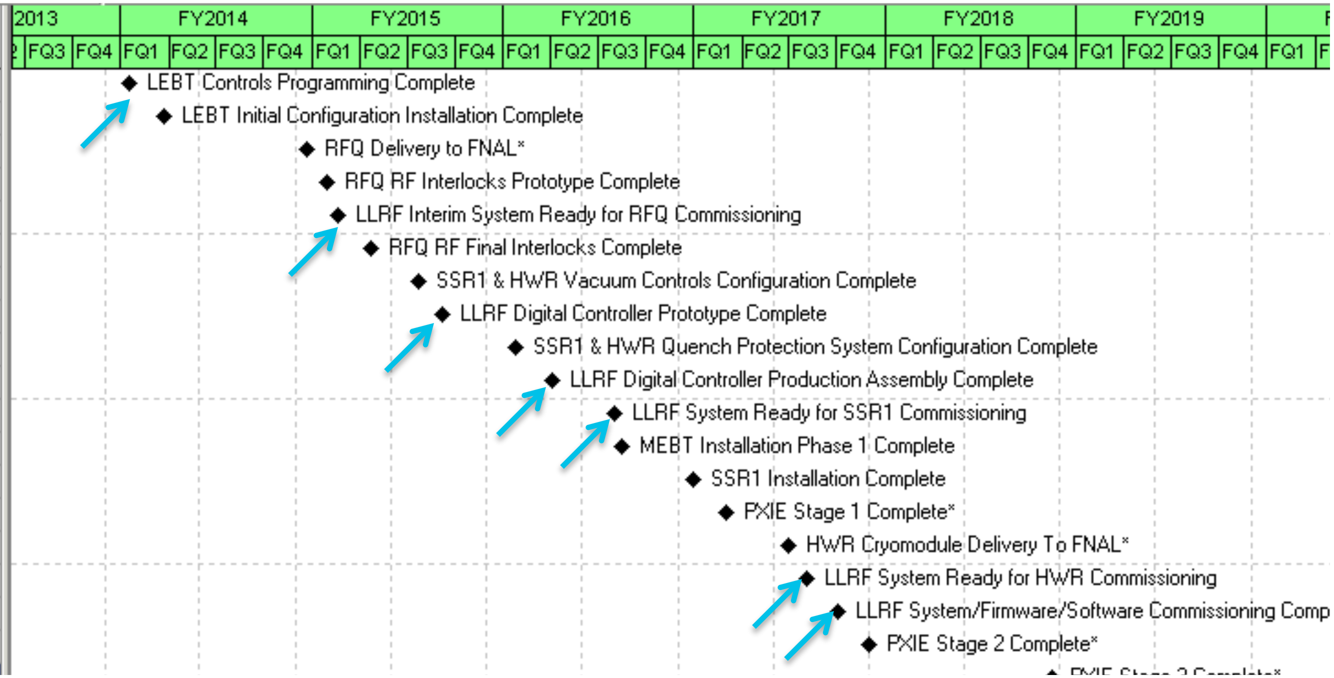
Parameters of RF Cavities

#	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

* Amplitude of transverse kick

Major Milestones

Activity Name	Finish
LEBT Controls Programming Complete	17-Oct-13
LEBT Initial Configuration Installation Compl...	23-Dec-13
RFQ Delivery to FNAL*	22-Sep-14
RFQ RF Interlocks Prototype Complete	31-Oct-14
LLRF Interim System Ready for RFQ Commi...	19-Nov-14
RFQ RF Final Interlocks Complete	22-Jan-15
SSR1 & HWR Vacuum Controls Configurati...	24-Apr-15
LLRF Digital Controller Prototype Complete	08-Jun-15
SSR1 & HWR Quench Protection System C...	27-Oct-15
LLRF Digital Controller Production Assembly...	05-Jan-16
LLRF System Ready for SSR1 Commissioning	03-May-16
MEBT Installation Phase 1 Complete	17-May-16
SSR1 Installation Complete	29-Sep-16
PXIE Stage 1 Complete*	30-Nov-16
HWR Cryomodule Delivery To FNAL*	31-Mar-17*
LLRF System Ready for HWR Commissioning	03-May-17
LLRF System/Firmware/Software Commissi...	03-Jul-17
PXIE Stage 2 Complete*	30-Aug-17*



RF Power budget and Ql

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.

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	-	-	-

Total cavity detuning budget including LFD

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

May need real-time feedback during pulse

Ongoing cavity design efforts to lower these numbers

Discussions are in progress about optimizing amplifiers and QL for pulsed operation