Design & Implementation of the LLRF System for LCLS-II

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LLRF 2017

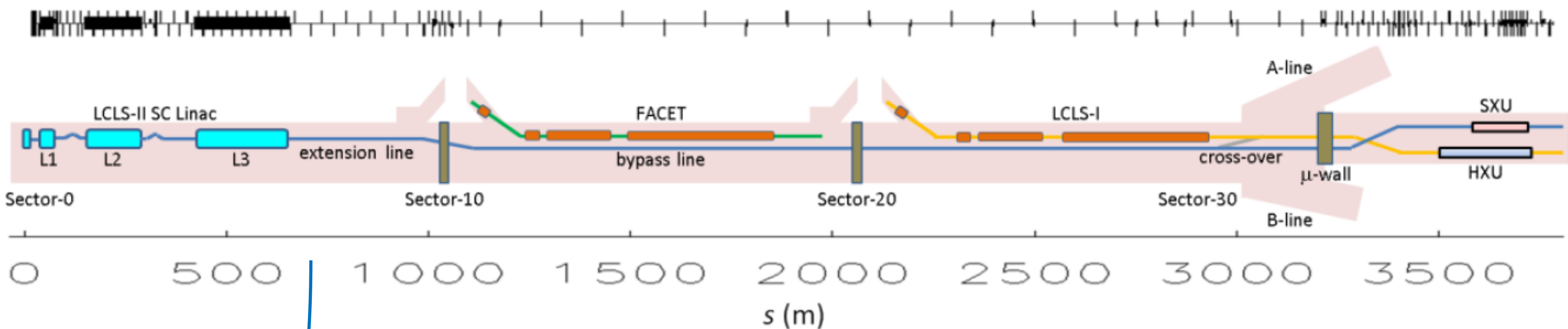
October 16, 2017

Outline

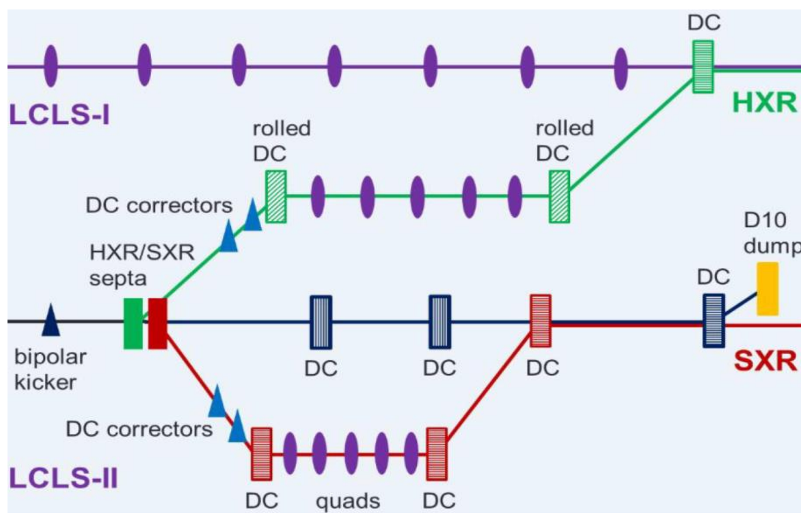
- LCLS – II
- LCLS – II LLRF Requirements/Parameters
- LLRF Team
- LLRF Design
- Testing efforts
- Production
- Six Month Outlook

LCLS-II

- **The Linac Coherent Light Source (LCLS-II), in Menlo Park, CA is designed produce a 4 GeV electron beam at high repetition rate (up to 1 MHz) for Soft X-ray (SXU) and Hard X-ray (HXU) Undulators**
- **In order to accomplish this, SLAC will install 280 1.3 GHz superconducting RF cavities in the first third of the 2-mile accelerator housing**
- **Superconducting RF is new for SLAC – much partner lab help is needed!**



2 - 4.5 GeV, 1 MHz electron source

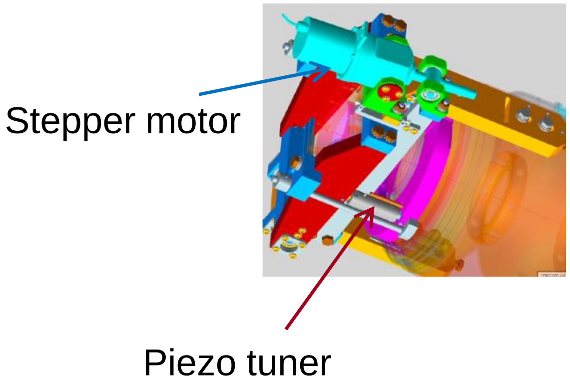


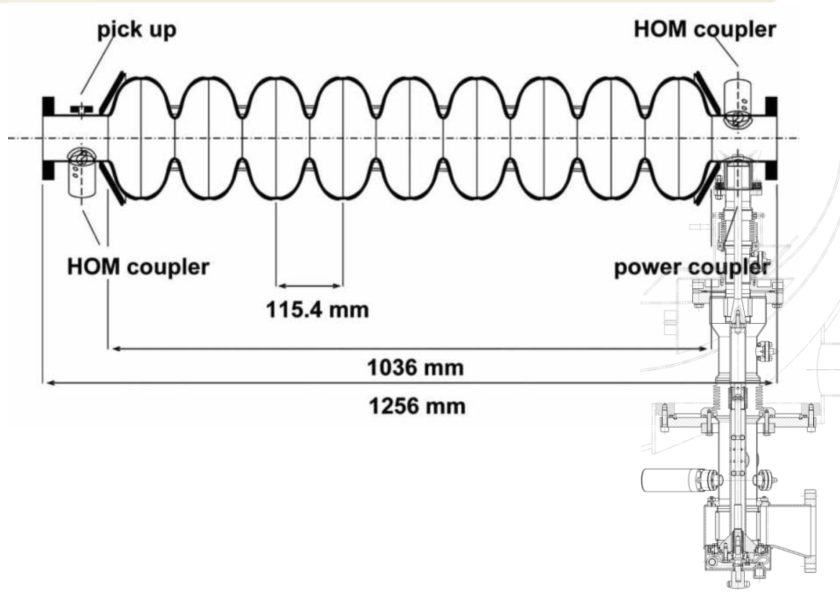
4 – 13 keV photons, 120Hz

1 – 5 keV photons, 1 MHz

0.2 – 1.3 keV photons, 1MHz

LCLS-II SC cavities

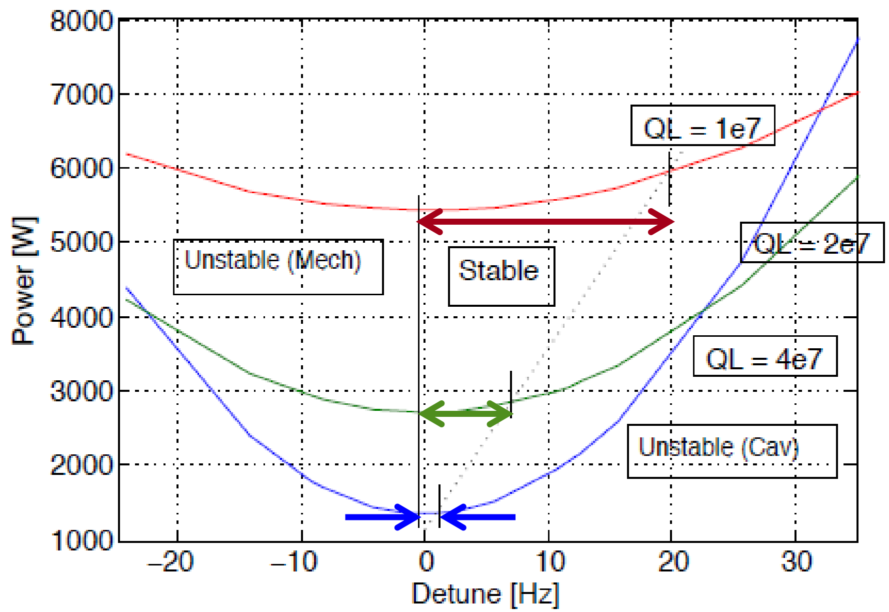




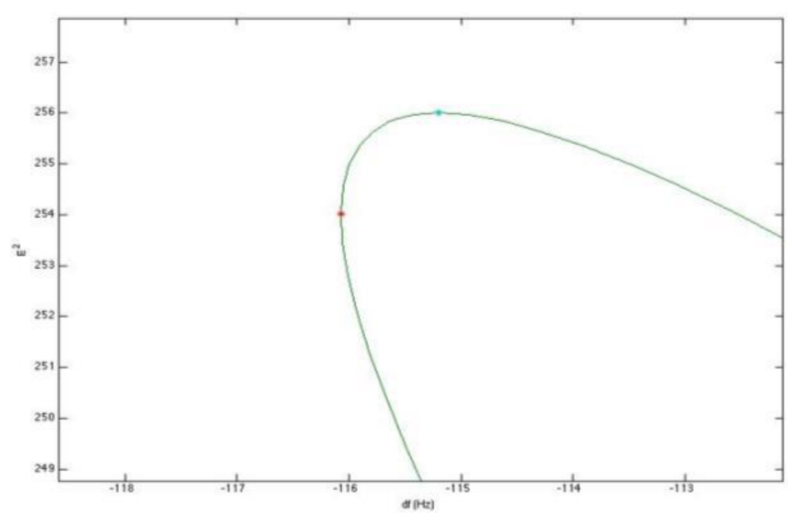
9 – cell Tesla style (baseline)		Spec
RF frequency	f_{RF}	1.3 GHz
Average gradient	E_{acc}	16 MV/m
Cavity Quality factor (unloaded)	Q_0	2.7×10^{10}
Cavity Quality factor (loaded)	Q_L	4.1×10^{7}
RF power per cavity	P_{cav}	3.8 kW

Single Source Single Cavity

- Main concern with one source driving multiple cavities is the gradient instability during (pseudo) open loop operation due to Lorentz force detuning
- Due to high Q_L design, LCLS – II opted for SSSC, individual cavity LLRF control, SSAs, and many *(280)* LLRF systems
- Lower complexity field control per RF system
- Single point of failure, 1 klystron for 48 cavities, also a large concern



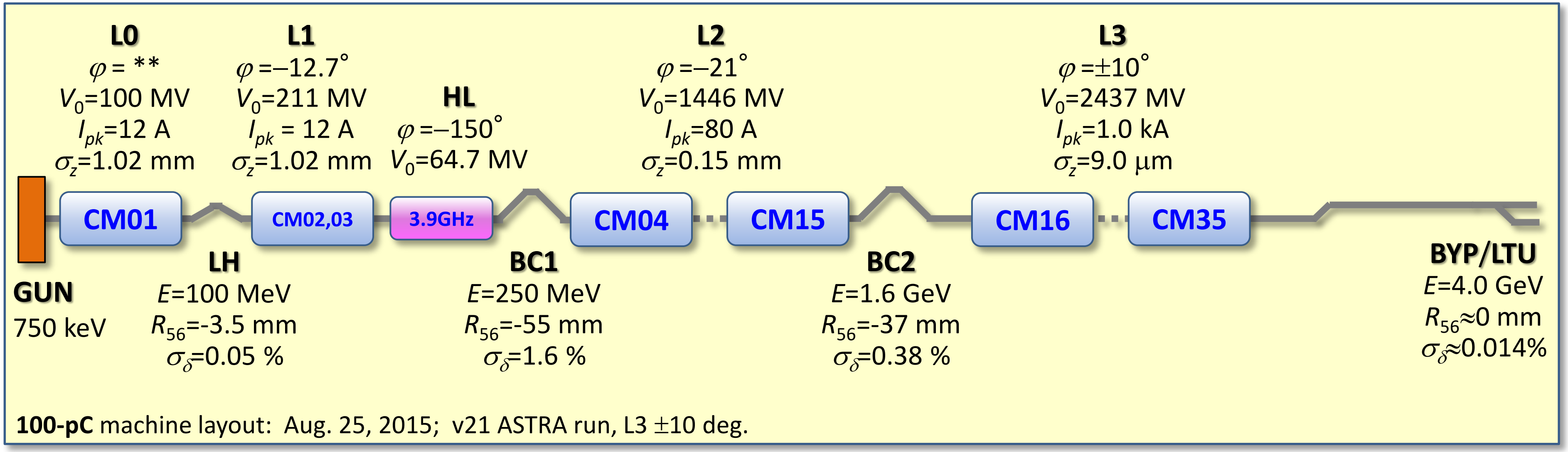
Gradient Squared vs Detuning



C Rivetta

LCLS-II LINAC RF Requirements

Required Field Control is derived from the linac energy spread and beam jitter tolerances at the undulator.



LCLS-II LINAC

Cavity Field Control Design Specification

- **For the time period > 1 Hz : 0.01% and 0.01º**
- **For the time period < 1Hz: 5.0% and 5.0º**
  - **The LLRF system will eventually be supported Beam Based Feedback system.**
  - **LLRF System is designed to be BBF ready**

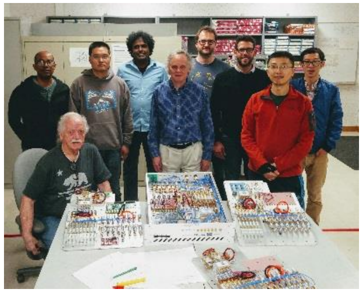
LLRF Team

SLAC

Management,
MO/LO, Software
M. Boyes
A. McCollough
B. Hong*
G. Brown*
A. Benwell
Jorge Diaz
Mark Petree
Jerry Hovey
Sonya Hoobler*
Allan Johnson
Rick Kelly
Dave Steele

LBNL

Design Lead,
Digitizer, Digital
Carrier, Firmware,
Gun & Buncher
L. Doolittle
G. Huang
C. Serrano
K. Campbell
V. Vytla
J. Jones
Q. Du
J. Greer
Y. Xu



FNAL

Up & Down
Converters,
Piezo Driver, 3.9 GHz
B. Chase
E. Cullerton
J. Einstein
Dan Klepec

JLAB

Interlocks,
Stepper Driver,
Power supply
R. Bachimanchi
C. Hovater
D. Seidman
O. Kumar

Project CAM: Matt Boyes
Technical Lead: Larry Doolittle
RF Gun/Buncher Lead: Gang Huang
SLAC LLRF Integration: Andy Benwell

***Not Shown**

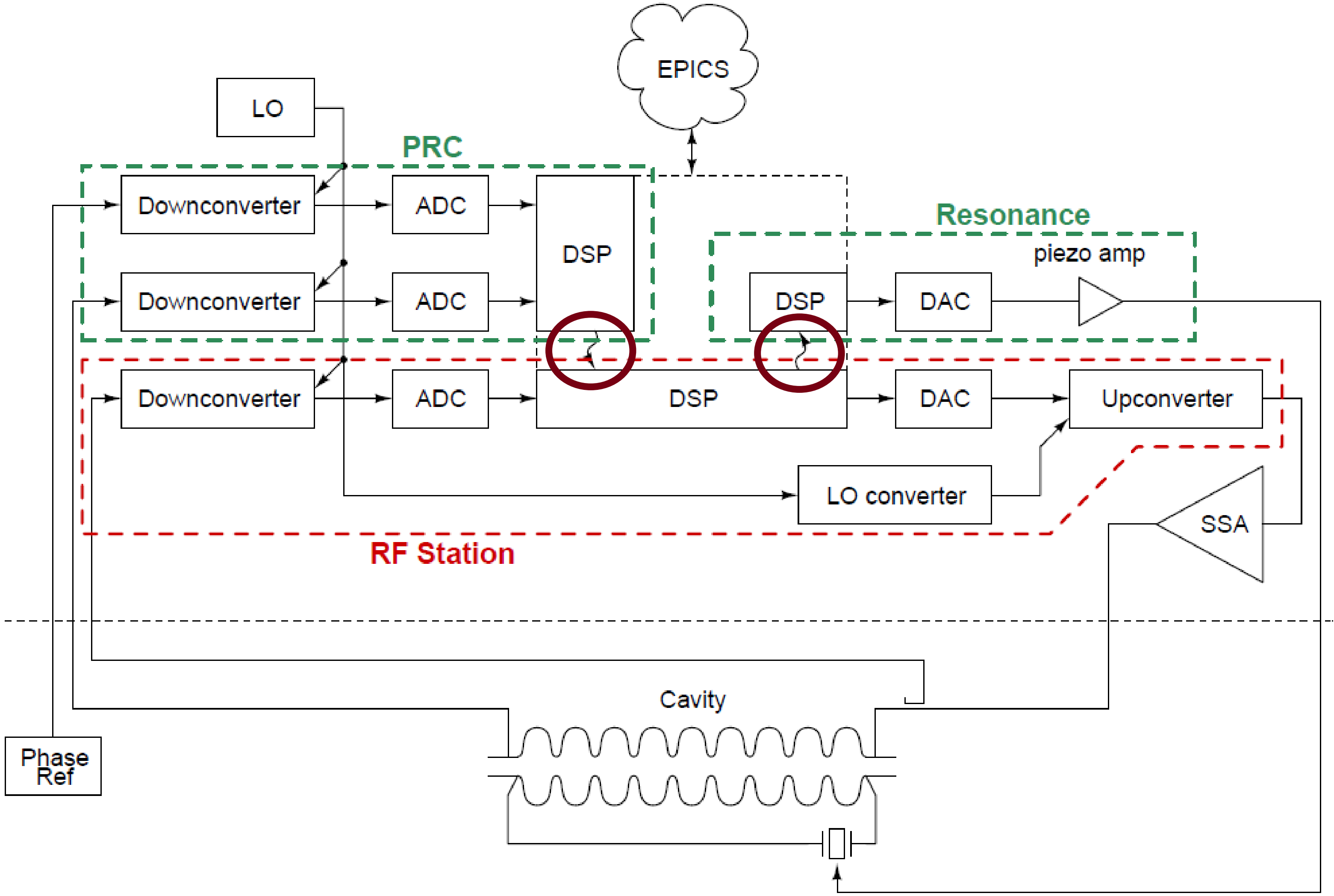
Design Philosophy

- **Requirements (0.01º/0.01%) demand ultra low noise design.**
  - Keep noise generators far from critical components i.e. no fans in RF chassis!
  - High channel to channel isolation > 80 dB
    - Isolate cavity signals from drive signals
  - Receiver noise floors < -150 dBc/Hz
  - Low group delay to enable high gain

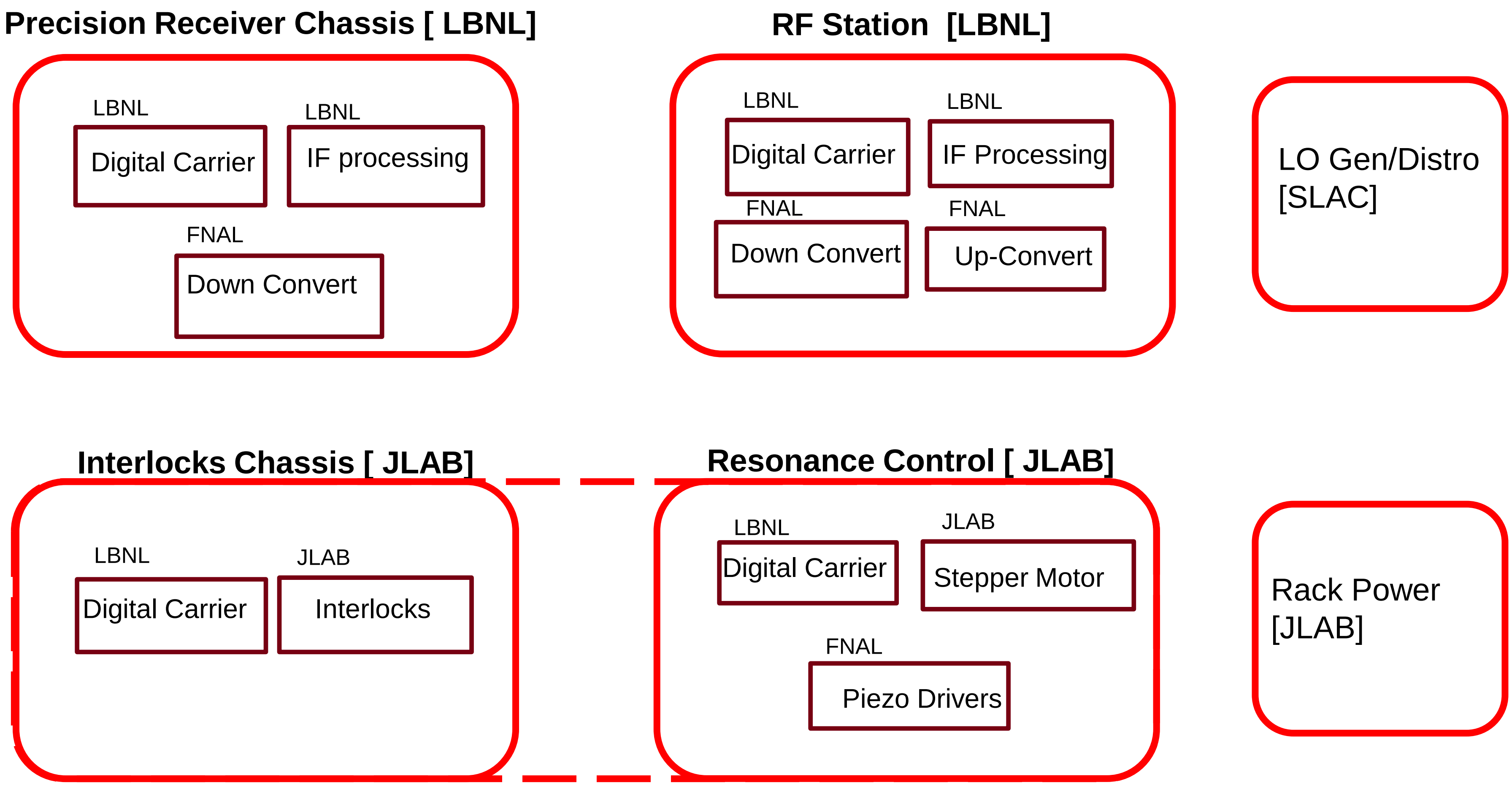
- **Value Engineering: Build upon what has been done in the immediate past and what is commercially available.**
  - Designs based on LBNL/FNAL/JLAB recent work
  - Components (Mixers/ADCs/Amps) commercially available (Mini-circuits/TI)
  - NAD system based around a common carrier board
  - 3.9 GHz and RF Gun/Buncher use common components

- **Resources: Make the best use of a multi-Lab project**
  - Partner Labs do what they do best with the resources available.
  - Develop SLAC personnel for ownership as the project progresses

Simplified Hardware Architecture

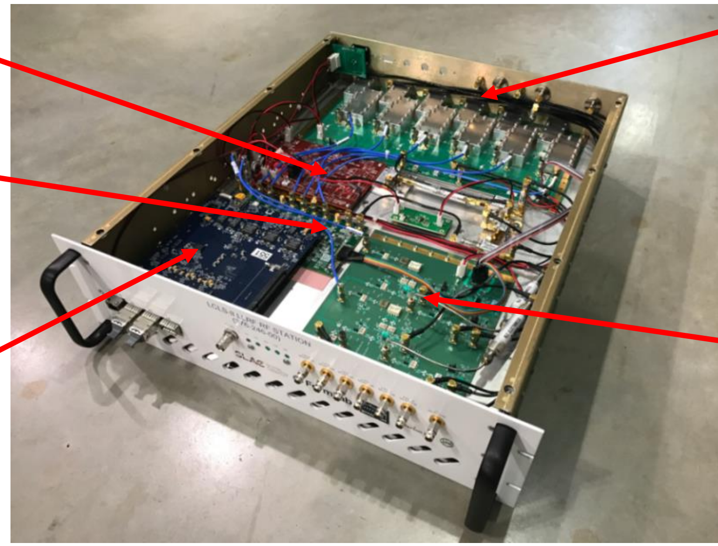


LLRF System Components: Multi Lab Collaboration Effort



- **Digital Carrier Board is the same for 4 sub-components**
- **IF Processor Board is the same for PRC and RF Station**
- **Down-Converter is same for PRC and RF Station**

RF Station and Precision Receiver



<u>Design Features</u>

- Split IF design
  - 20 MHz for downconversion – low crosstalk through digitizer
  - 145 MHz for upconversion – better band pass filter design
- 94.3 MHz clock rate – cavity passband within first Nyquist zone
- 7/33 ratio for IF to ADC clock – yields near IQ sampling

RFS/PRC Isolation Test Results

SLAC measurements (re)confirm good design with production type chassis

Downconversion Channel Isolation after Digitizer

Input Channel	CH1 (dBFS)	CH2 (dBFS)	CH3 (dBFS)	CH4 (dBFS)	CH5 (dBFS)	CH6 (dBFS)
1	0	-81.9	-106	-102	-105	-94.0
2	-87.9	0	-107	-107	-108	-104
3	-99.1	-104	0	-81.3	-97.6	-89.3
4	-102	-101	-86.8	0	-96.0	-90.7
5	-112	-105	-99.1	-96.4	0	-87.1
6	-97.6	-104	-94.8	-95.3	-82.0	0

Upconversion - Downconversion Isolation after Digitizer

Setpoint	CH1 (dBm)		CH2 (dBm)		Digitized input signals					
-A	Output	Monitor	Output	Monitor	Ch1	Ch2	Ch3	Ch4	Ch5	Ch6
0	-90.10	-93.00	-90.20	-94.00	-112.9	-116.9	-123.2	-116.2	-117.2	-116.4
2000	-13.21	-32.31	-87.21	-97.12	-113.7	-109.9	-107.0	-109.7	-112.2	-120.1
4000	-13.13	-32.20	-86.71	-92.31	-119.1	-111.7	-107.8	-112.1	-120.8	-115.9
8000	-1.30	-20.32	-77.11	-85.41	-105.4	-108.7	-99.71	-103.7	-106.3	-108.3
16000	4.71	-14.59	-71.41	-78.33	-106.2	-110.2	-93.32	-106.4	-103.5	-100.5
32000	10.67	-8.45	-65.52	-73.21	-100.8	-105.2	-88.92	-96.00	-99.91	-95.61

Resonance Control Chassis

One resonance chassis controls four cavities

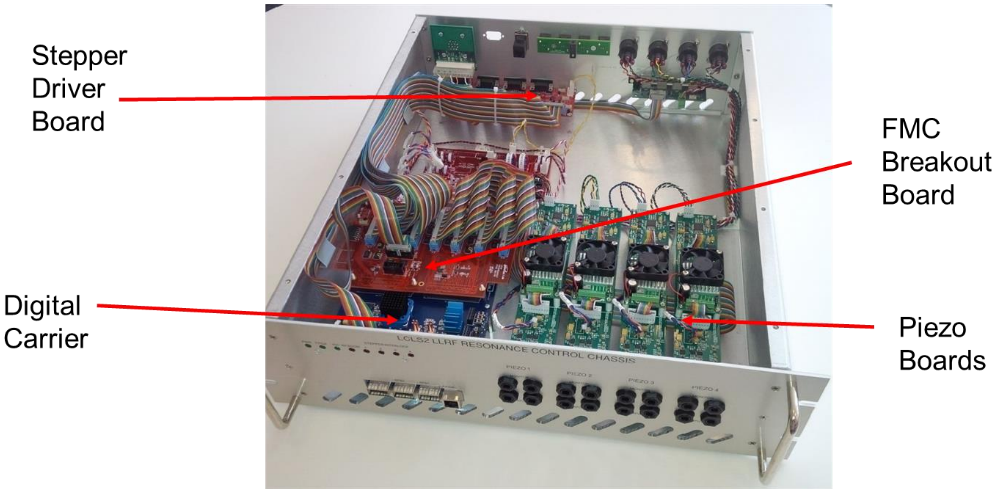
- Utilizes LLRF common Digital Carrier board for control and communication

Stepper (JLAB)

- Four Stepper Drivers
- Uses a commercial Stepper IC

Piezo Drive (FNAL)

- Four independent low noise piezo amplifiers
- 0-100V differential output (50 V to ground – low risk to tuners)
- Uses a commercial piezo IC.
- **Active compensation ready!**



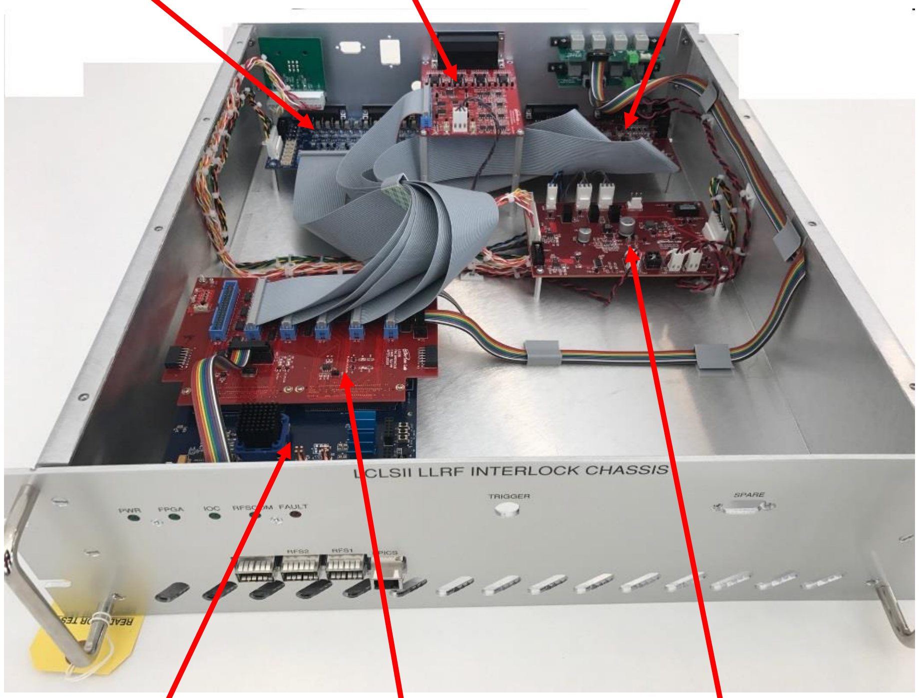
- **Has been used to tune LCLS – II cavities in SEL**
- **Has demonstrated GDR at 12 MV/m**

Interlock Chassis

One interlock chassis protects four cavities

- Uses LLRF common Digital Carrier board for control and communication
- Interlocks RF on
    - Temperatures for couplers and stepper motors
    - Arc detection
    - Infrared
    - Coupler Field Emission
- Will verify detuned status during power outage

- **Has been reliably protecting cryomodules at JLAB since January '17**



LLRF Testing on Cryomodules

- LLRF installed at the FNAL CMTS
  - Presently capable of four cavity operation
  - Second rack for full cryomodule is installed, cables being run.
- JLAB soon to repurpose Low Energy Recirculating Facility (LERF) for LCLS 2 cryomodule testing
  - 4 full LLRF racks (2 cryomodules) scheduled for installation in February 2018

Power Supply

Resonance Chassis

RF Station 1

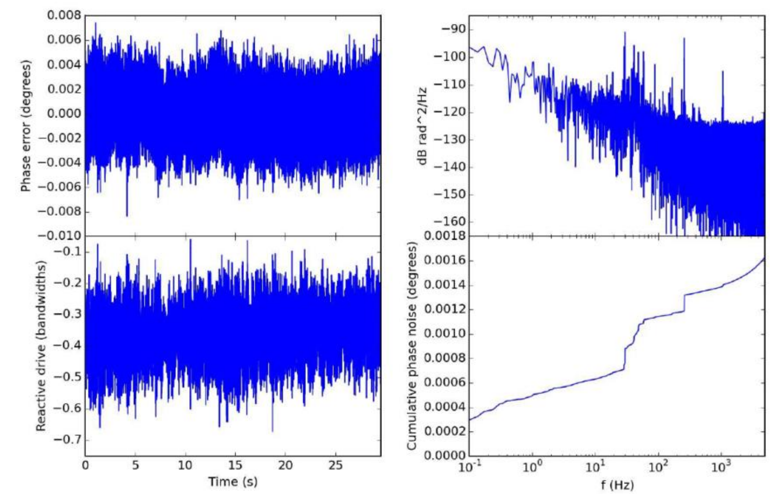
RF Station 2

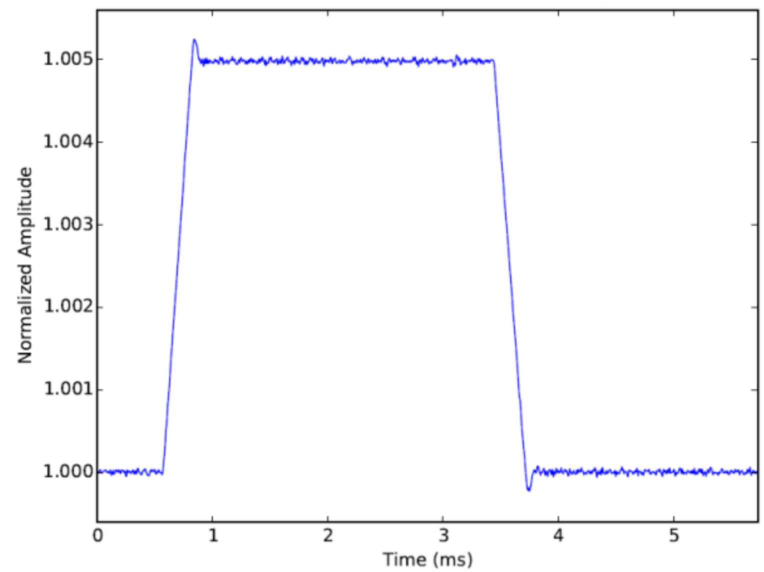
Precision Receiver Chassis

System Level Testing

<u>Tests performed on pCM and CM02</u>

- Controlled cavities 1 through 4 simultaneously in SEL and GDR mode on CM02
- Automated cavity turn-on scripts find phase in SEL and ramp amplitude, even with significant low field detuning
- In-loop and out-of-loop measurements – can measure and run within target regulation
- P & I gain scans - values set manually, but scans produce reasonable values for transient responses



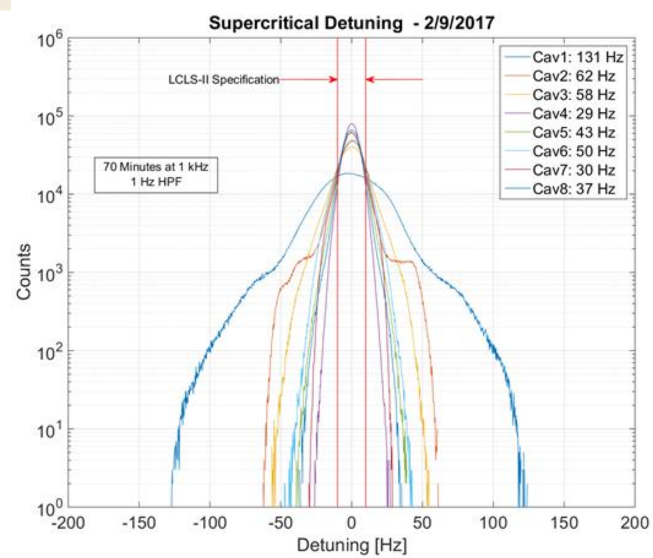


See talk by L. Doolittle – Today!

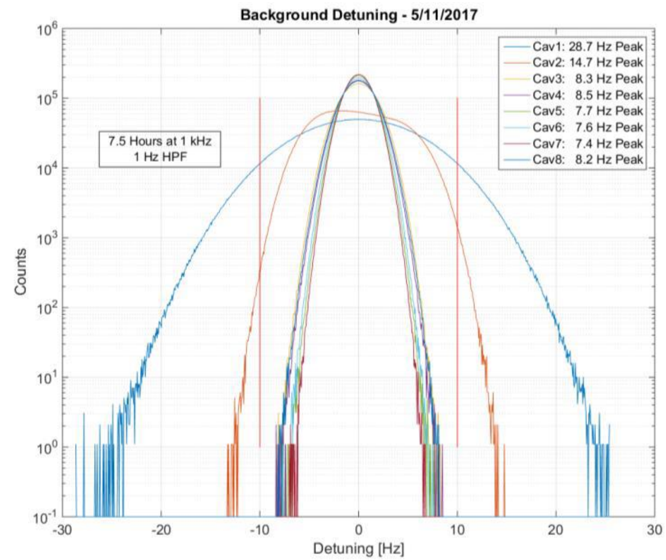
Active Microphonic Compensation

- During pCM tests Thermal Acoustic Oscillations (TAO) were observed
- Microphonic detuning in the 30 to 50 Hz peak range. (Specification is 10 Hz peak)
- Mitigation made by combination of:
  - **Mechanical design changes in CM cryogenics piping**
  - **Development of active resonance controls**

LLRF + FNAL Microphonics Mitigation group
- Warren Schappert
- Yuriy Pischanikov
- Jeremiah Holzbauer



pCM

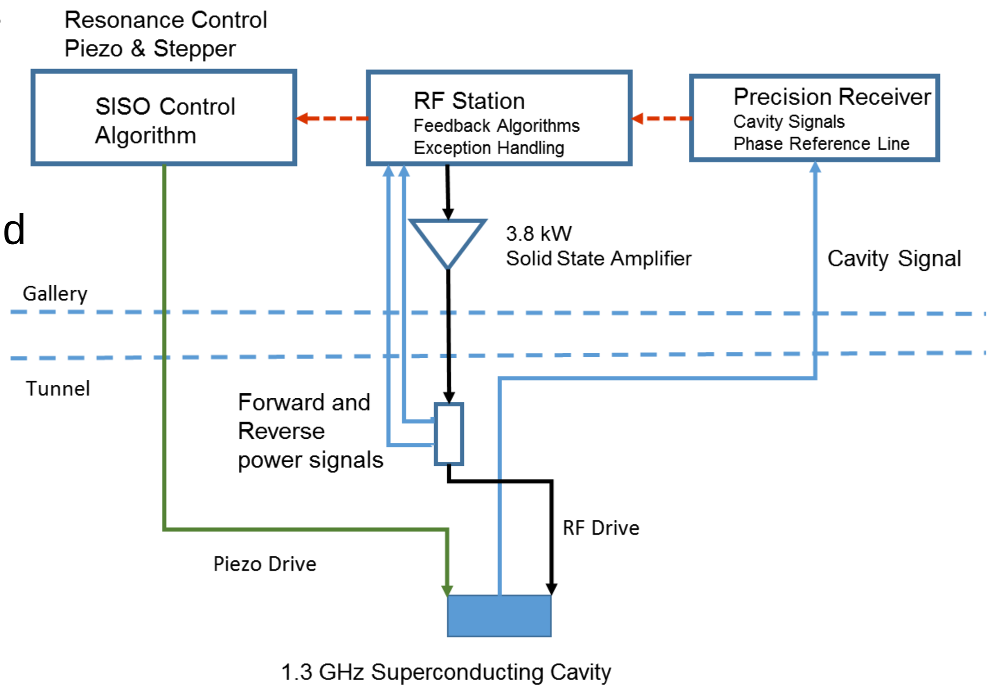


After Improvements

F1.3-02

Active Microphonic Compensation

- Resonance chassis actuates piezo tuners to compensate pre-characterized microphonics sources
- SISO control algorithm using standard field control path
- Updates made only to firmware (and software) only – no hardware re-design
- Aiming for a reduction of microphonic detuning by a factor of 3



See talk by J. Einstein – Thursday!

Meanwhile…

SLAC is also ramping up testing effort for production hardware

- Full set of hardware in production test rack
- Temperature studies on running equipment
- EPICS interfaces, waveform readouts

Production Builds

SLAC is gearing up to manage production and installation

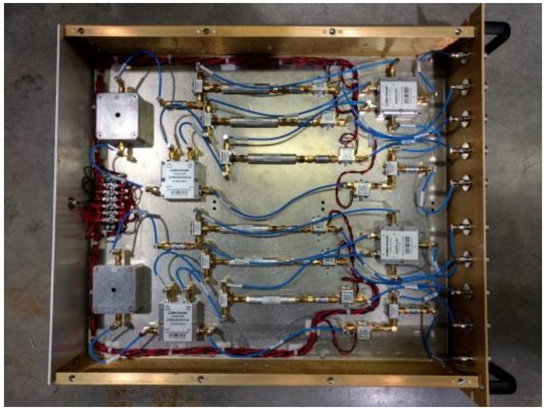
- Sensitive chassis PCBs may be sent (directly) to partner labs for testing in existing test benches

- Outside assembly houses have been evaluated to assemble:
  1. LO distribution
  2. Power Supply
  3. Resonance Control
  4. Interlock (if needed)
  5. Optical Patch Panel
- RF Station and PRC assembled in house (at SLAC) based on cost and readiness

Production Testing

Testing has begun on all completed chassis at SLAC

- RFS, PRC, Resonance Control will be evaluated at SLAC with test benches
- Piezo and Stepper motor loads will be used to pre-test resonance control (also for housing cable testing)
- In lieu of a cryomodule, rack system functionality tested with cavity emulators



Sixth Month Look Ahead

- LLRF system hardware is finalized
  - Firmware tweaks will continue
- Continue testing active compensation algorithm for microphonics
- Start production runs of all hardware
- Finalize chassis test bench procedures for production chassis
- Continue EPICS interface
- Commission LLRF for Gun and Buncher

FI – Gràcies

Special thanks to all of the

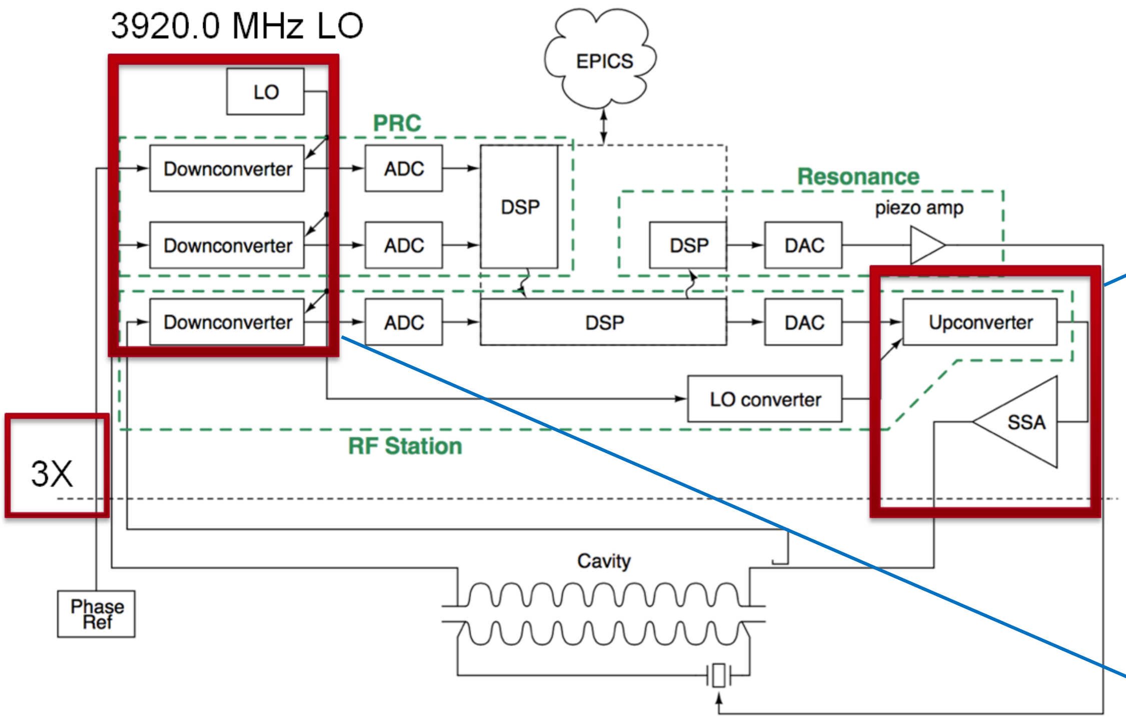
LLRF team members

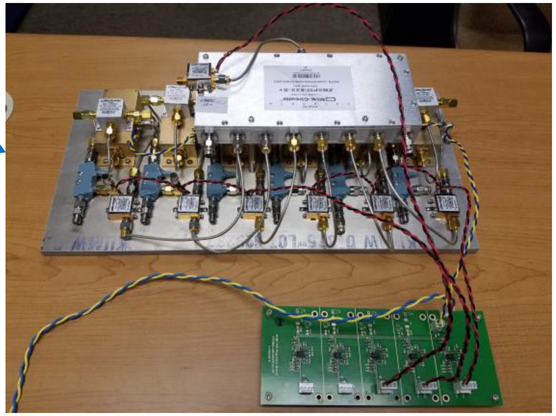
at SLAC, LBNL, FNAL and JLAB.

Field Control System

- **Precision Receiver Chassis (PRC)**
  - Exclusively for cavity signals
    - Processes four cavity signals
    - Two Phase Reference Line signals
    - Design utilizes common industry ICs and RF components (**nothing exotic**)
  - Fiber communication with RF station
    - Ensures **high Isolation** needed for gains necessary for 0.01°/0.01%
- **RF Station (RFS)**
  - Receiver/Transmitter
    - Generates independent RF signal for 2 cavities
    - Processes Forward, Reverse and SSA Drive signals
    - Detune calculation, PI loop control
- **Resonance Control**
  - Piezo Control, Stepper Motor Control
    - Four cavities per chassis
    - Same FPGA/carrier as RFS/PRC
    - Temperature Monitoring
    - Interlock processing

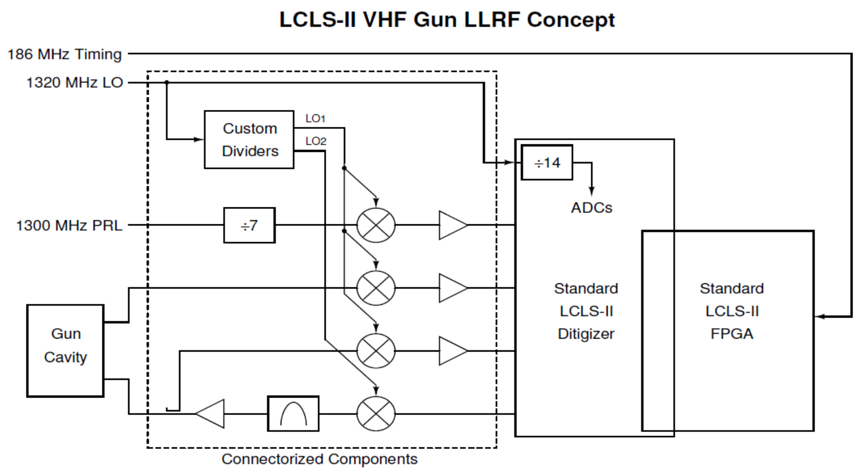
3.9 GHz 4 Cavity Control – similar to 1.3 GHz

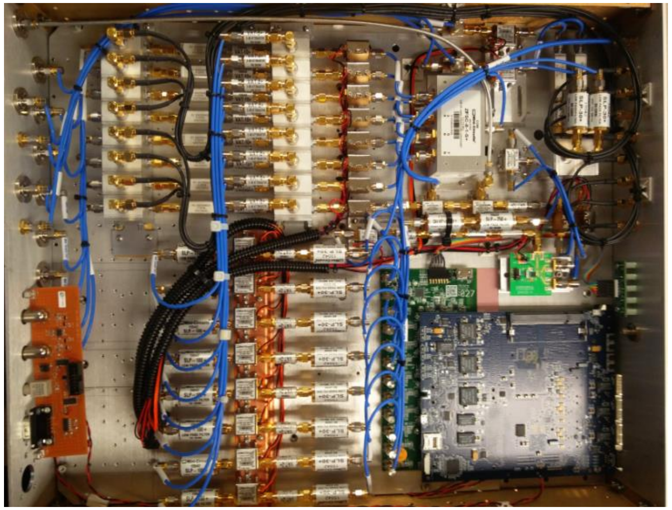




- Bench prototype for the up and down converters is built and tested showing proof of capability
- Full prototype system is being developed and will be tested at CMTS in spring or summer 2018

Early Injector Commissioning (EIC)





- Gun LLRF system
  - Hardware designed, fabricated, and bench tested
  - Similar to 1.3 GHz with connectorized components
  - Chassis test results exceed design specifications
- Buncher LLRF system
  - Uses the same PRC/RFS as the SRF system
  - Chassis are allocated
- Firmware for both Gun and Buncher are under development for EIC deployment

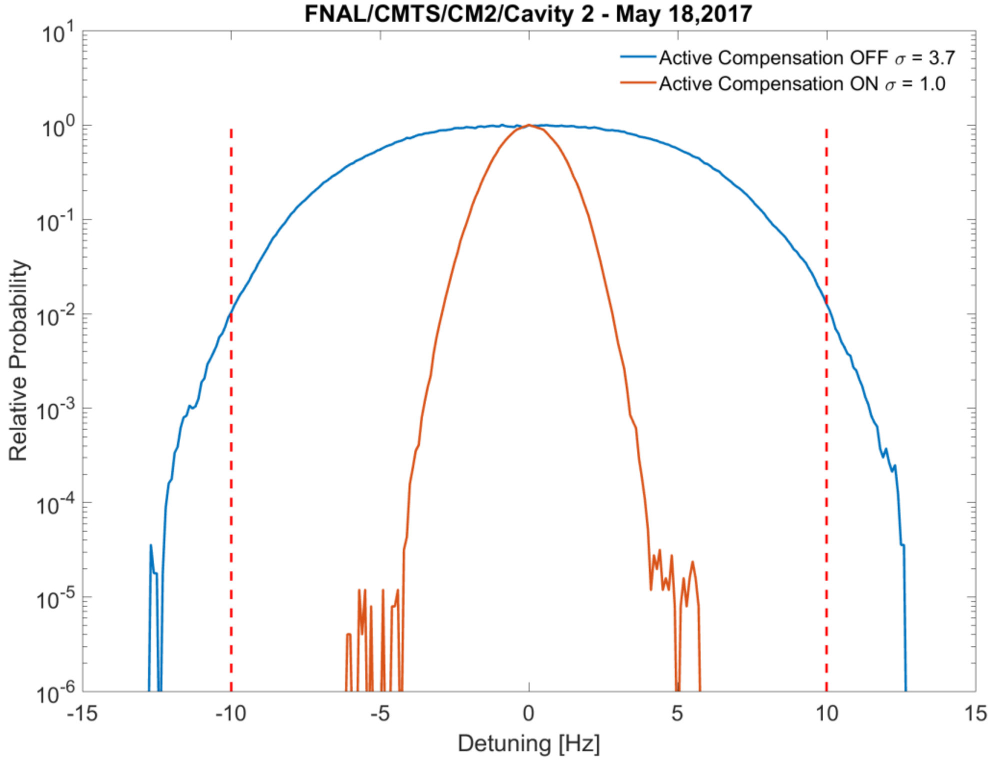
LERF

- Low Energy Recirculating Facility (LERF) at JLAB repurposed to simultaneously test 2 production CMs while using LCLS2 RF hardware
- LERF will require 4 complete LLRF racks and LO distribution
- Installation in February ‘18 to be ready for May system checkout

- LLRF *gives*: four loaded early production LLRF racks will be sent to JLAB (*to be returned for LCLS-II installation)*
- LLRF *gets*: the chance to perform a complete early system installation and practice for commissioning LCLS2

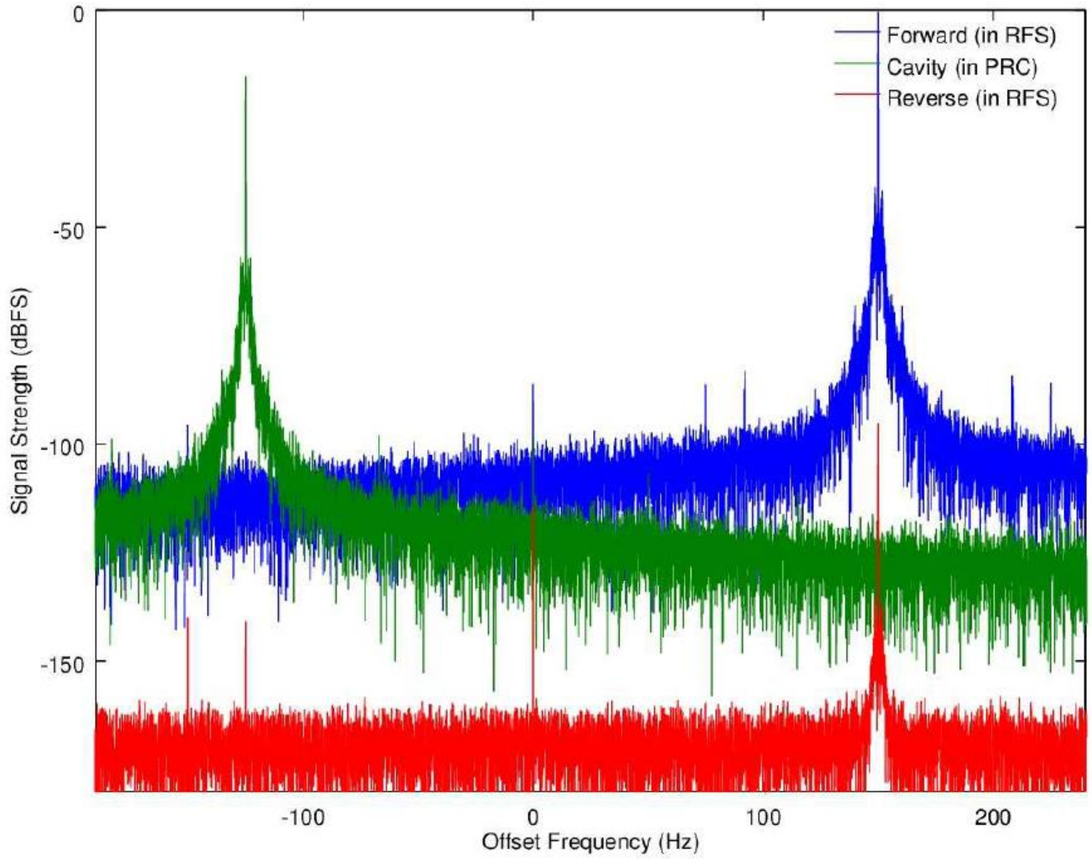
Demonstration of Technique

- Bank of band-pass filters will be used for active compensation
- Data shown for four filters with manually tuned coefficients
- RMS detuning reduced by factor of 3.7, over the factor of 3 specified
- Stability and optimization studies under way



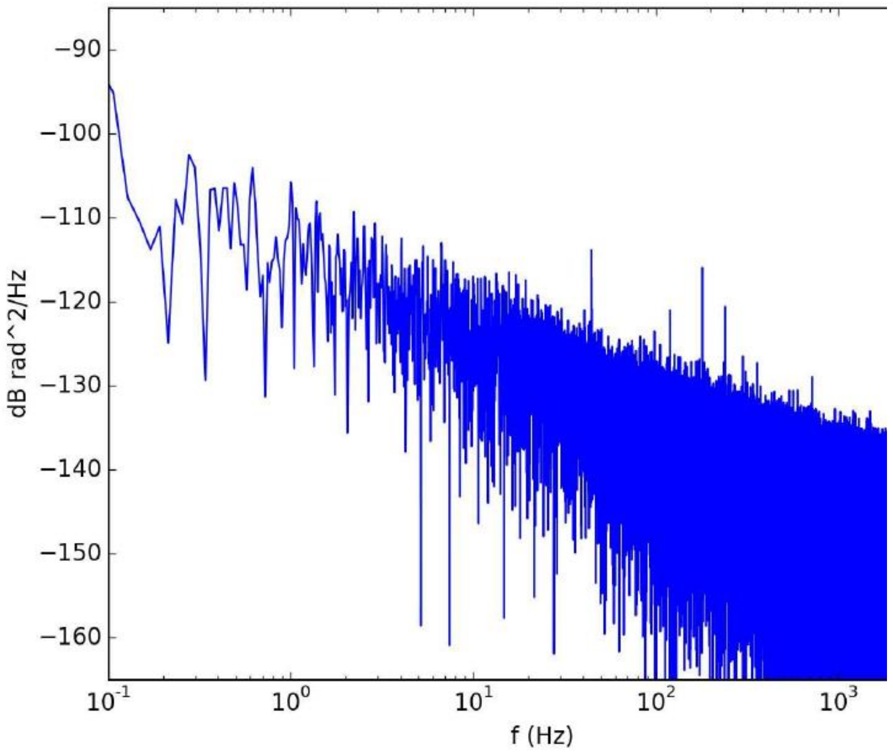
J. Holzbauer: Microphonics Measurement & Mitigation - 9/27

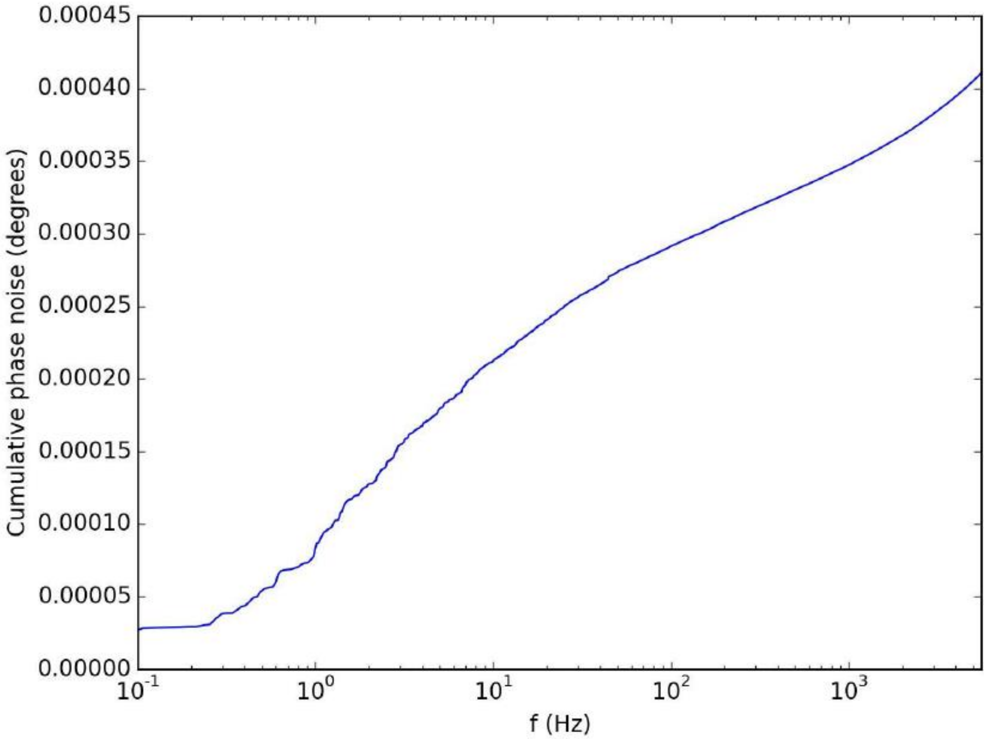
PRC/RFS Isolation Test Results



Intrachassis crosstalk -90 dB, interchassis crosstalk better than -120 dB

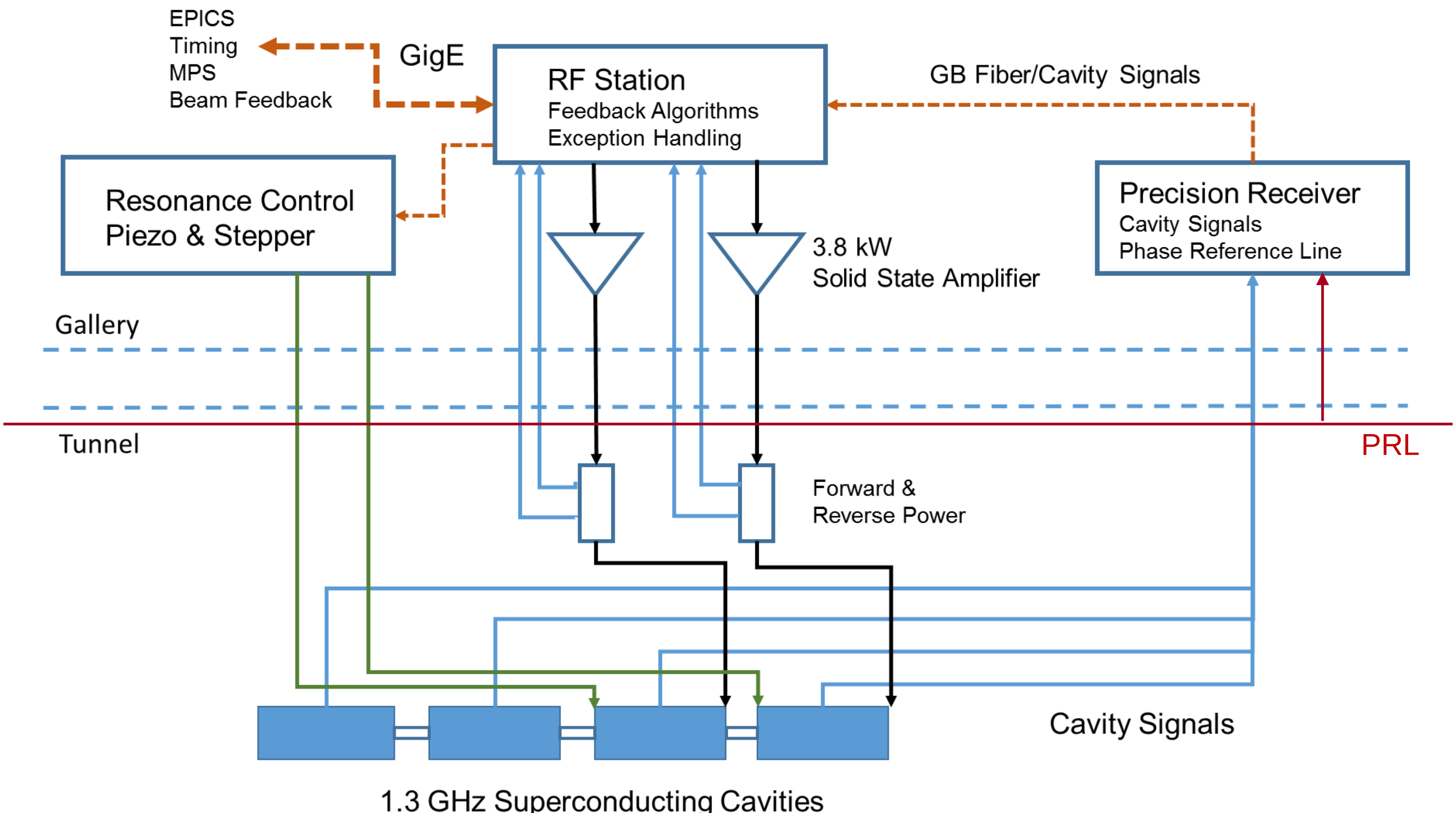
PRC/RFS Phase Noise





Measured at 1300 MHz with passive splitter and two PRC channels

LLRF Architecture*



*Cryomodule Interlocks not shown