121.03.04 - Low Level Radio Frequency

SC1 - Accelerator Systems

Brian Chase

PIP-II IPR

4-6 December 2018

In partnership with:

- India/DAE
- Italy/INFN
- UK/STFC
- France/CEA/Irfu, CNRS/IN2P3

Outline

- Scope/Deliverables
  - (Including In-Kind Contributions)
- Requirements
- Interfaces
- Preliminary Design, Maturity
- Technical Progress to Date
- ESH&Q
- Risks and Mitigations
- Summary

About Me:

- Brian Chase:
  - L3 Manager for Low Level RF
- Relevant experience
  - 30+ years in accelerator technology development
  - Responsible for LLRF in 400 MeV Linac, Main Injector, Tevatron, Recycler, SRF LLRF at: A0, FAST, ILC,
  - Low Level RF group leader with an experienced team
    - LCLS-II design team and cryomodule test, STC, HTS

LLRF and RFPI Systems required for PIP-II

Charge #2

	Frequency [MHz]	Number of RF cavities	Amplifiers per Cavity	Amplifier power [kW]	Number of 4-cavity stations
RFQ	162.5	1	2	75	1 (special)
Bunching Cavities	162.5	4	1	3	1
HWRs	162.5	8	1	3,7	2
SSR1s	325	16	1	7	4
SSR2s	325	35	1	20	9
LB650s	650	33	1	40	9
HB650s	650	24	1	70	6

- LLRF hardware is compatible for all cavity frequencies and is repeated in racks controlling four cavities
- Each frequency section has its own Phase Reference Line and Local Oscillator
- Beam Pattern Generator and Booster RF Reference for beam transfers

Scope and Deliverables

Charge #2

- *Provide all hardware, firmware and expert software utilities to satisfy system requirements.*
- *PIP2IT and Test Stands LLRF including*
  - RF field control for the warm front end and SRF cryomodules
  - Resonance control for the RFQ, half wave resonators
  - Resonance control support for SSR and elliptical cavities
  - RF Interlocks for all SRF systems
- *PIP-II LLRF Hardware Deliverables:*
  - (72) 8 Channel down-converter
  - (42) 4 Channel up-converter
  - (72) Field control chassis
  - (40) Resonance control chassis
  - (70) Rack power supplies
  - (1+ spare components) Reference line system
  - (2) Beam pattern generator
  - (116 cav) SRF Interlocks
  - 182.5, 345, 670, 1320 MHz LO Distribution Chassis

Scope and Deliverables

Charge #2

- *PIP-II LLRF Software/Firmware Deliverables:*
  - Data acquisition firmware
  - Field control firmware
  - Resonance control integration
  - Chopper Waveform Generator
  - Beam-based energy stabilization jointly with Instrumentation and Booster
  - RF Interlocks firmware
  - Expert systems software for all systems

WBS L3 LLRF System Requirements

Charge #2

- LLRF: Maintain proper amplitude and phase control of cavities in order to meet requirements for phase-space painting into the booster
  - Provide system to deliver amplitude stability to 0.01% and phase stability to 0.01°
  - Provide for resonance control for RFQ and SRF cavities
  - Provide distributed phase-locked reference signals at 1300 MHz (for instrumentation), 650 MHz, 325 MHz, and 162.5 MHz.
  - Provide CW RF with pulsed beam operation mode

- Chopper Driver: Beam pattern generator control
  - Provide injection RF and marker for beam transfer to Booster
  - Define chopper pattern, drive and regulate beam chopper waveforms

- RFPI: Provide RF protection and interlocks
  - Provide protection to cavities, and RF systems from RF related issues

- All Systems provide diagnostic waveforms through the control system and interface with the Machine Protection System (MPS)

FRS, TRS, BOE, Risk, etc.

Charge #2

System Level Documents			
Item	Doc-DB number	T.C Number	rf.bd../Systems/PIP-II/
RF Power Integration PM and Coordination	986-v14	N/A	N/A
RF Integration Interlocks	1001-v18	N/A	N/A
RF integration Reference Line	998-v12	N/A	N/A
RF integration LLRF for PIP-II	995-v12	N/A	N/A
RF Integration LLRF for Test Infrastructure	992-v12	N/A	N/A
RF Integration LLRF for PIP2IT	989-v19	N/A	N/A
LLRF ICD Accelerator Facility	N/A	ED0007714	N/A
LLRF ICD Control System	N/A	ED0007269	N/A
LLRF ICD Conventional Facilities	N/A	ED0007790	N/A
LLRF ICD CryoModule	N/A	ED0007247	N/A
LLRF ICD Install and Commisioning	N/A	ED0007715	N/A
LLRF ICD Intrumentation	N/A	ED0007717	N/A
LLRF ICD Warm Front End	N/A	ED0007303	N/A
LLRF ICD L3 List	N/A	ED0007707	N/A
LLRF ICD L3 ID matrix	N/A	ED0007573	N/A
LLRF ICD Template	N/A	ED0007719	N/A
LLRF/Interlock Rack Diagrams (png)	N/A	N/A	Schematics and Diagrams/
Building Facilities LLRF Systems Block Diagram.png	N/A	N/A	Schematics and Diagrams/
Simulation and Modeling FRS	N/A	ED0005050	N/A
LLRF Station FRS	N/A	ED0005054	N/A
LLRF, PIP-II, Technical Specification for the Interfaces of the LLRF Systems		N/A	ICD documents/
Genreal MO and PRL documents		N/A	RF Distribution System

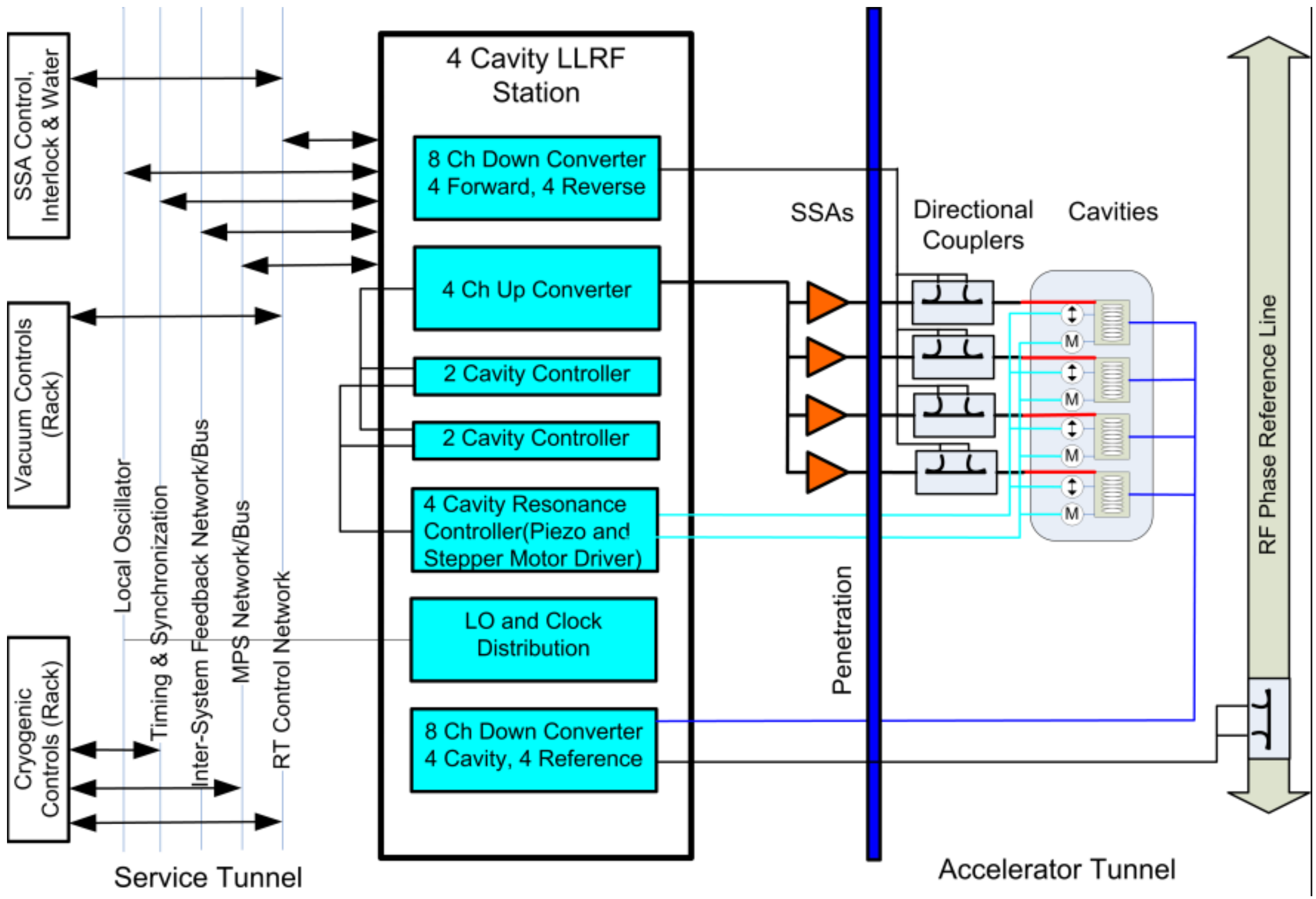
LLRF RACK EQUIPMENT	Team Center Documents					BOE Documents	
Item	FRS	TRS	Risk Assesment	Acceptance Document	TC Supporting Documents	BOE Supporting Documents	BOE Document Location (rf.bd/..)
LLRF 4-Channel Upconverter Chassis	ED0004089	ED0005163	ED0005206	ED0007874	ED0006242	BOM with price quotes for all parts	rf.bd/Projects/LLRF/Components/Hardware/Chassis Modules/PIP-II 8 Channel Downconverter/Rev A/BOM/8 Channel Downconverter BOM_10
LLRF 8-Channel Downconverter Chassis	ED0004190	ED0005166	ED0005207	ED0007875	ED0005207	BOM with price quotes for all parts	rf.bd/Projects/LLRF/Components/Hardware/Chassis Modules/PIP-II 4 Channel Upconverter/Rev C/BOM/4 Channel Upconverter BOM_10
LLRF FPGA Controller Chassis	N/A	N/A	N/A	N/A	N/A	N/A	N/A
---Digitizer Board	ED0004195	ED0007284	ED0005696	ED0007823	ED0006245		
---FPGA Board	ED0004193	ED0005793	ED0005683		ED0006244		
LLRF Resonance Control Chassis	ED0004191	ED0005782	ED0005694	ED0007822	ED0007493		
LLRF 182.5 MHz LO Distribution Chassis	N/A	N/A	N/A	N/A	N/A	BOM with price quotes or estimates for a	rf.bd/Projects/LLRF/Components/Hardware/Chassis Modules/PIP-II 4 LO Distibution Chassi/PIP-II LO Distribution Chassis BOM
LLRF 345 MHz LO Distribution Chassis	N/A	N/A	N/A	N/A	N/A	BOM with price quotes or estimates for a	rf.bd/Projects/LLRF/Components/Hardware/Chassis Modules/PIP-II 4 LO Distibution Chassi/PIP-II LO Distribution Chassis BOM
LLRF 670 MHz LO Distribution Chassis	N/A	N/A	N/A	N/A	N/A	BOM with price quotes or estimates for a	rf.bd/Projects/LLRF/Components/Hardware/Chassis Modules/PIP-II 4 LO Distibution Chassi/PIP-II LO Distribution Chassis BOM
LLRF 1320 MHz CLK Distribution Chassis	N/A	N/A	N/A	N/A	N/A	BOM with price quotes or estimates for a	rf.bd/Projects/LLRF/Components/Hardware/Chassis Modules/PIP-II 4 LO Distibution Chassi/PIP-II LO Distribution Chassis BOM
LLRF Downconverter Temperature Controller						BOM with price quotes or estimates for a	rf.bd/Projects/LLRF/Components/Hardware/Chassis Modules/Dual Temperature Controller/Board/Rev B/BOM/Dual Temperature Controller Bo
LLRF RF Power Supply	ED0005055	ED0007283				BOM with price quotes or estimates for a	rf.bd/Projects/LLRF/Components/Hardware/Chassis Modules/Power Supply Breakout Panel/Power Supply Breakout Panel BOM
LLRF Controller Power Supply	ED0005055	ED0007283					
LLRF Resonance Control Power Supply	ED0005055	ED0007283					
Chopper Waveform Generator and Booster Sync							

MO AND PRECISION REFERENCE LINE							
Item	FRS	TRS	Risk Assesment	Acceptance Document	TC Supporting Documents	BOE Supporting Documents	Document Location
LLRF 162.5 MO Station Enclosure	ED0005057	ED0005164	ED0005696			BOM with price quotes or estimates for a	rf.bd/Projects/LLRF/System/PIP-II/RF Distribution System/RF Distibution System BOM
LLRF 325 MO Station Enclosure	N/A	N/A	N/A	N/A	N/A	BOM with price quotes or estimates for a	rf.bd/Projects/LLRF/System/PIP-II/RF Distribution System/RF Distibution System BOM
LLRF 650 MO Station Enclosuree	N/A	N/A	N/A	N/A	N/A	BOM with price quotes or estimates for a	rf.bd/Projects/LLRF/System/PIP-II/RF Distribution System/RF Distibution System BOM
Rack/Distribution/Spare Components	N/A	N/A	N/A	N/A	N/A		
Spare Components	N/A	N/A	N/A	N/A	N/A		

LLRF Interfaces

Charge #2

Interface documents are in Team Center-see previous slide



Preliminary Design and Design Maturity

Charge #1

- PIP2IT and STC LLRF and RFPI
  - warm front end is operational
  - HWR and SSR1 systems are either installed or in construction
  - still some firmware and software work still to do
  - will be ready for operations when the cryomodules are installed in 2019
- PIP-II LLRF and RFPI FNAL designs have some options
  - Up and downconverters – mature and should be stable
  - Reference line in prototype stage
  - FPGA based controller – somewhat dated and needs a new rev that is in progress
  - Resonance control will leverage off of LCLS-II
  - Pursuing collaboration with LBNL
  - India plans to contribute on the scale of 10% of the stations

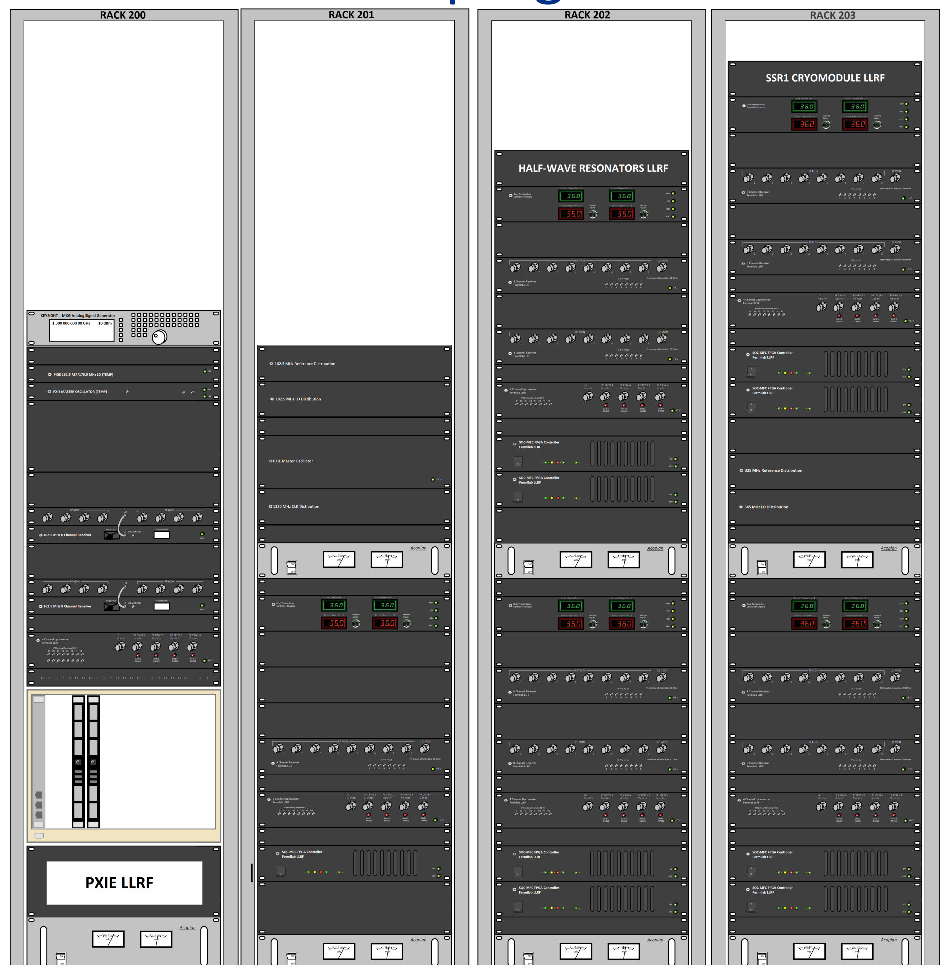
LLRF 650MHz Test Stand and PIP2 IT Racks

Charge #1

Installed at STC

Warm front end operational for 2 years

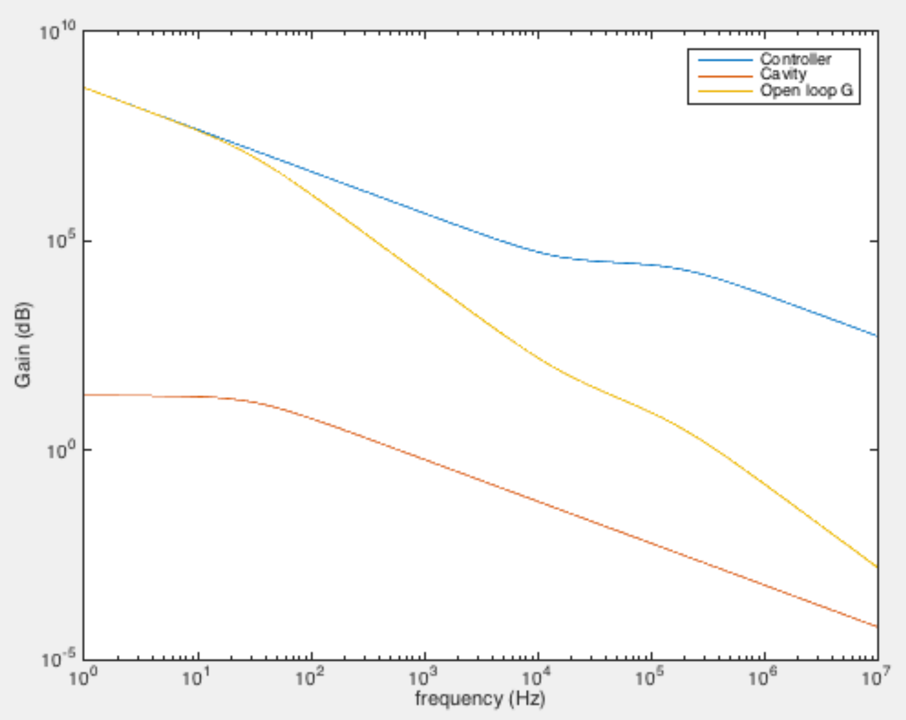
HWR and SSR1 in progress



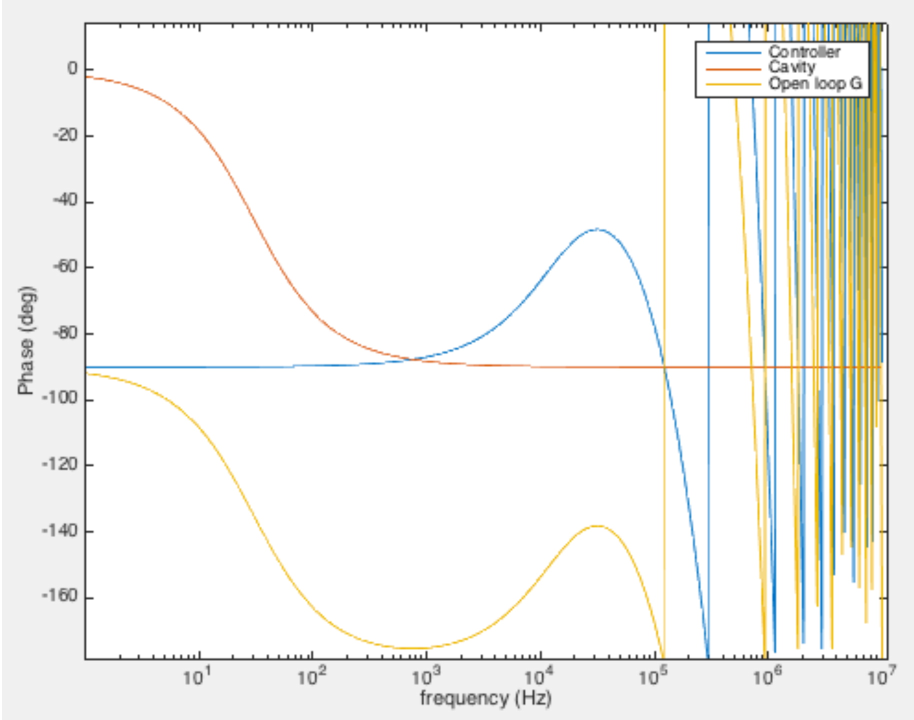
Progress to date: Open loop transfer function simulation of cavity and controller

Charge #1

Magnitude



Phase



Max gain

Closed-loop bandwidth: ~50 kHz

Control system zero: 15 kHz

Proportional gain: 1500

Integral gain: 14e+07

Nominal gain

Closed-loop bandwidth: ~25 kHz

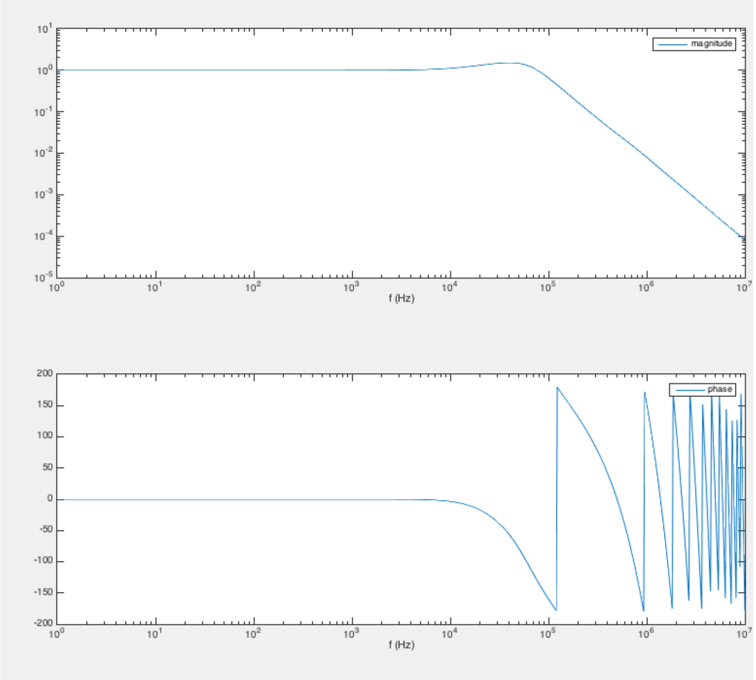
Proportional gain: 750

Integral gain: 7e+07

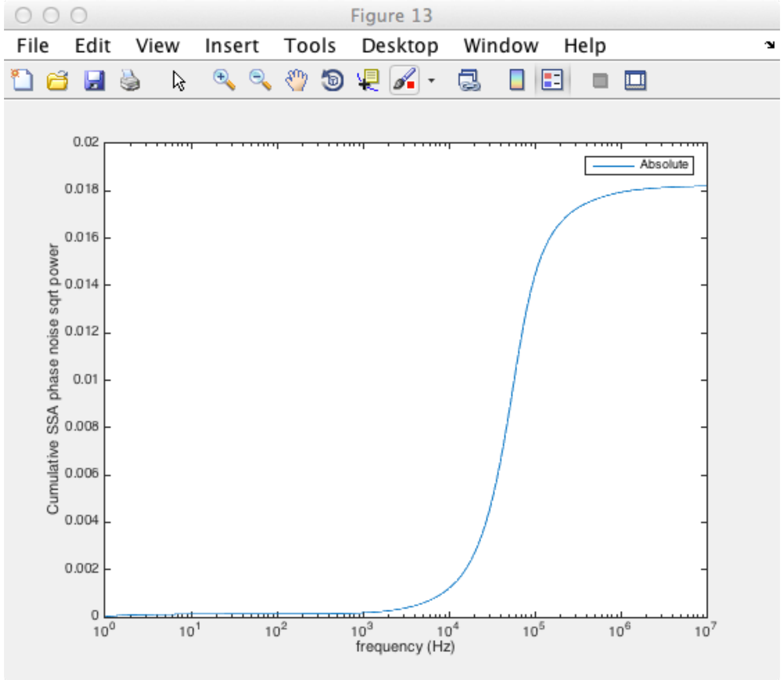
Progress to date: Total phase noise simulation to SSA from controller and oscillator

Charge #1

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°

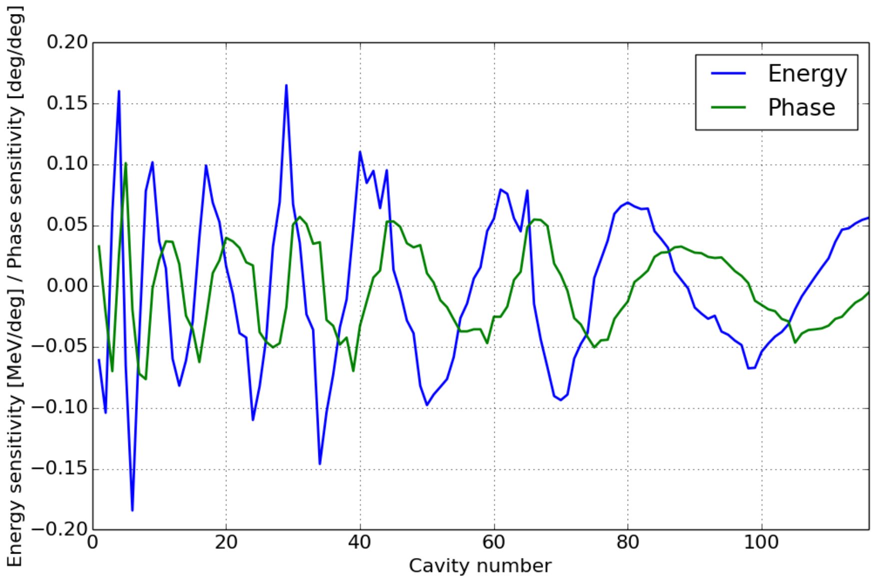
Code developed for LCLS-II
Larry Doolittle LBNL and FNAL

Fermilab
PIP-II
Proton Improvement Plan-II

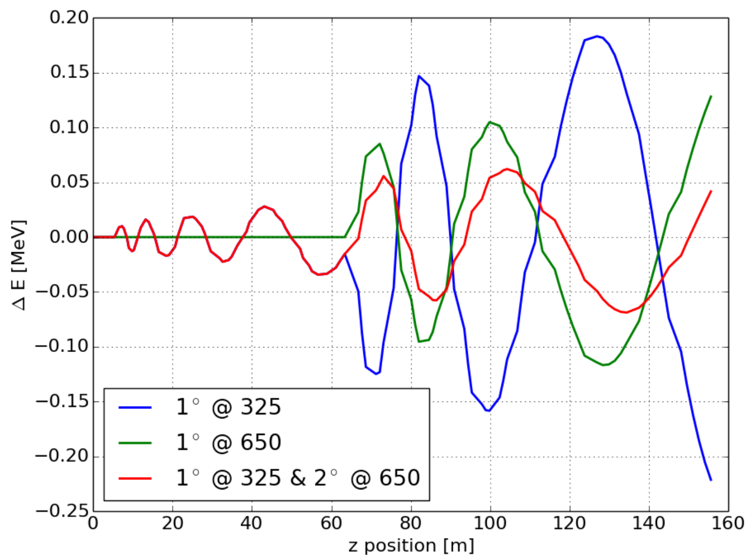
Progress to date: Phase-energy Stability Simulations

Charge #1

- Studying the amplitude and phase regulation requirements and their impact on the LLRF system
  - Study effects of perturbations on the cavities through beam simulations
  - Develop code that performs basic beam dynamics calculations as well as RF feedback simulations to study the interaction between the RF system



- Linac output energy sensitivity to single cavity phase errors
- Energy and phase errors could add up in a bad way but it is not probable



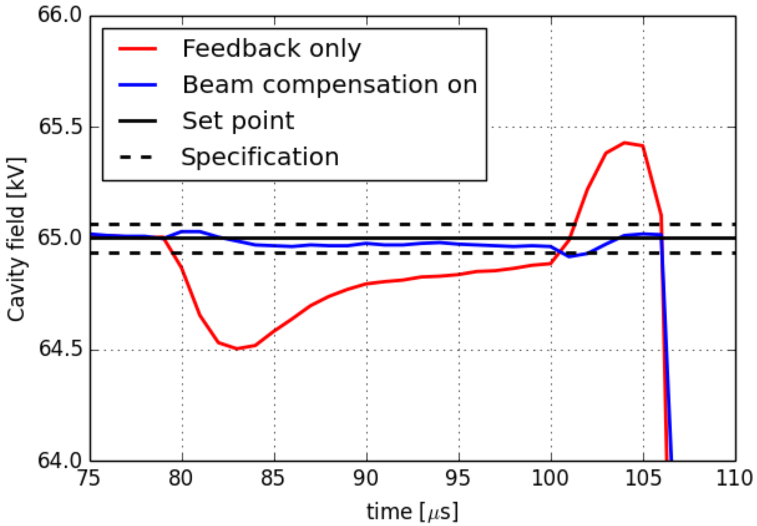
Linac output energy sensitivity to phase reference line phase errors at frequency transitions

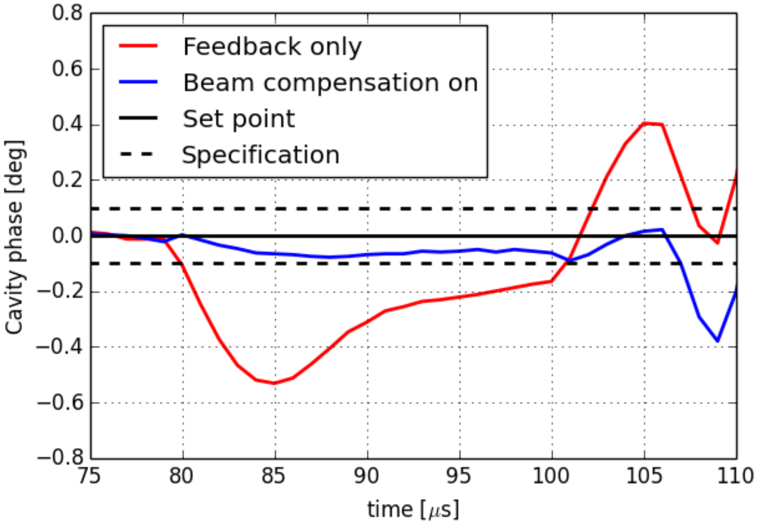
J. Edelen

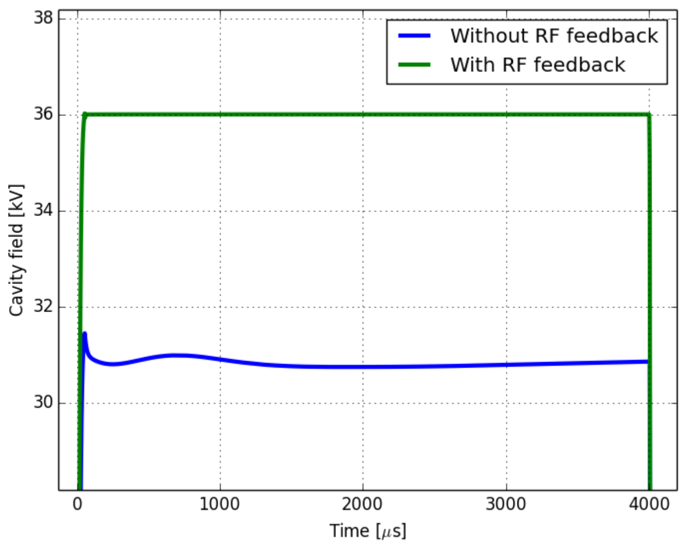
Progress to date – Regulation of Buncher Cav.

Charge #1

- With feed-forward beam compensation, the LLRF system achieves the regulation requirements for a short beam pulse
- Right: Demonstration of feed-forward beam loading compensation for a 20 microsecond beam pulse at 5mA
- Bottom: Illustration of amplifier transients mitigated by LLRF feedback



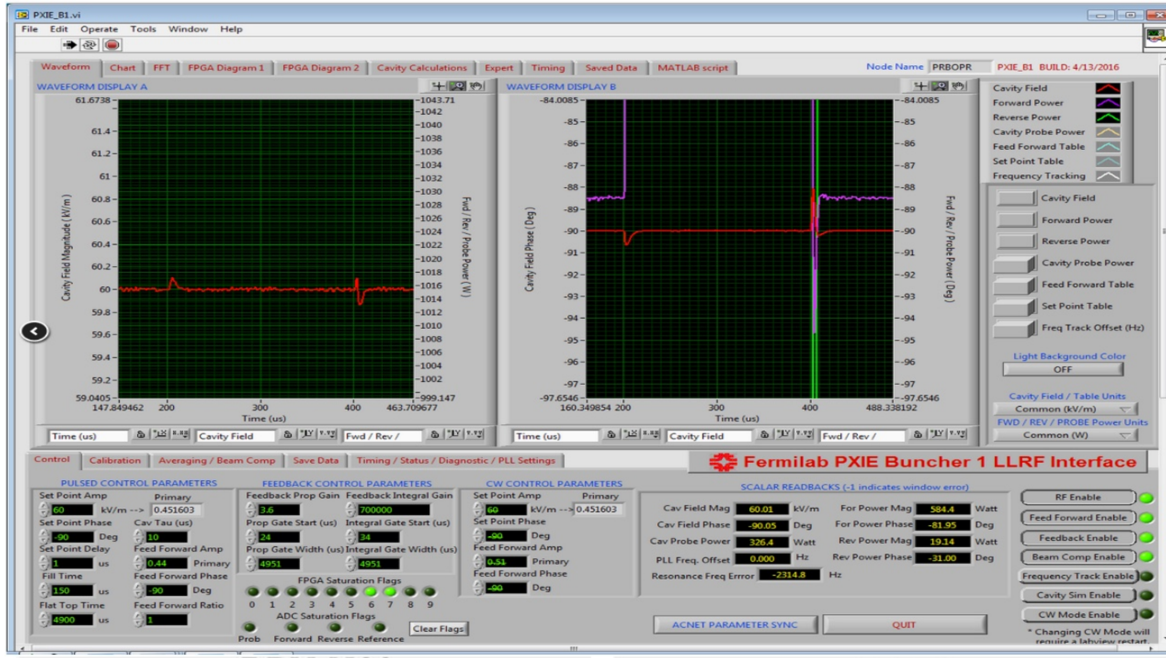


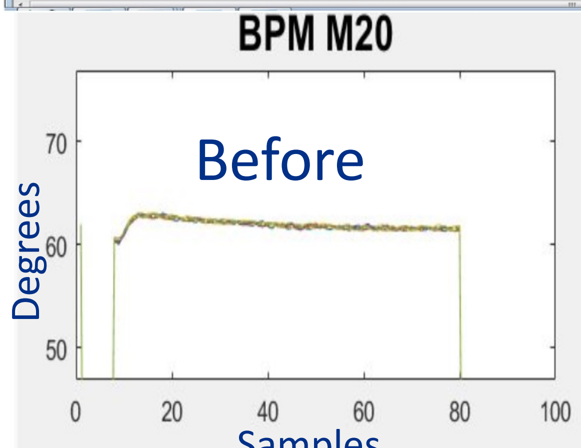


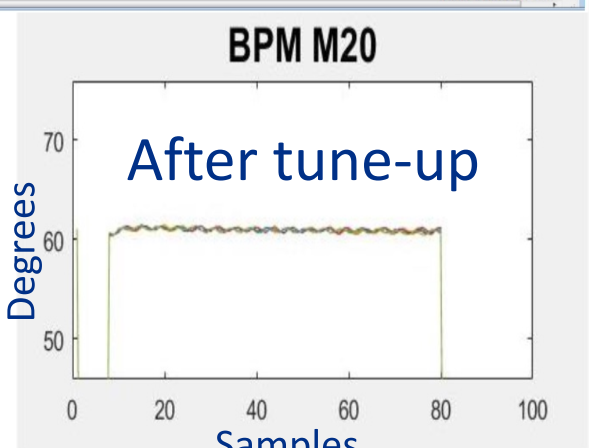
Beam Stability Study

Charge #1

- In a couple of hour shift we tuned up the feedback loops on the RFQ and Bunching cavities resulting in a much flatter beam energy profile shown in the BPM data
- Much more operational work to do







Charge #1

MSSR

(Minimal State-Space Realization)

- Hankel matrix of the impulse response represent a (non-minimal) realization of the system
- Singular Value Decomposition can decompose the Hankel matrix into a product of matrices of lower rank
- Lower rank matrices can be transformed into state space realization of lower dimension

http://www.dcsc.tudelft.nl/~bdeschutter/pub/rep/99_07.pdf

Many algorithms for minimal state space realization of impulse responses use the following block Hankel matrix:

$$H_{r,r'}(\mathcal{G}) = \begin{bmatrix} G_1 & G_2 & G_3 & \dots & G_{r'} \\ G_2 & G_3 & G_4 & \dots & G_{r'+1} \\ G_3 & G_4 & G_5 & \dots & G_{r'+2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ G_r & G_{r+1} & G_{r+2} & \dots & G_{r+r'-1} \end{bmatrix} .$$

Note that if (A, B, C, D) is a realization of the impulse response $\mathcal{G}$ then we have

$$H_{r,r'}(\mathcal{G}) = \mathcal{O}_r(C, A)\mathcal{C}_{r'}(A, B) \ .$$

We also define the shifted block Hankel matrix $\overline{H}_N(\mathcal{G})$ as

$$\overline{H}_{r,r'}(\mathcal{G}) = \begin{bmatrix} G_2 & G_3 & G_4 & \dots & G_{r'+1} \\ G_3 & G_4 & G_5 & \dots & G_{r'+2} \\ G_4 & G_5 & G_6 & \dots & G_{r'+3} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ G_{r+1} & G_{r+2} & G_{r+3} & \dots & G_{r+r'} \end{bmatrix} .$$

Find nonsingular matrices P and Q such that[4]

$$PH_{r,r}(\mathcal{G})Q = \begin{bmatrix} I_\rho & 0 \\ 0 & 0 \end{bmatrix} .$$

Now define

$$\begin{aligned} A &= E_{\rho,rl} P \overline{H}_{r,r}(\mathcal{G}) Q E^T_{\rho,rm} \\ B &= E_{\rho,rl} P H_{r,r}(\mathcal{G}) E^T_{m,rm} \\ C &= E_{l,rl} H_{r,r}(\mathcal{G}) Q E^T_{\rho,rm} \\ D &= G_0 \end{aligned}$$

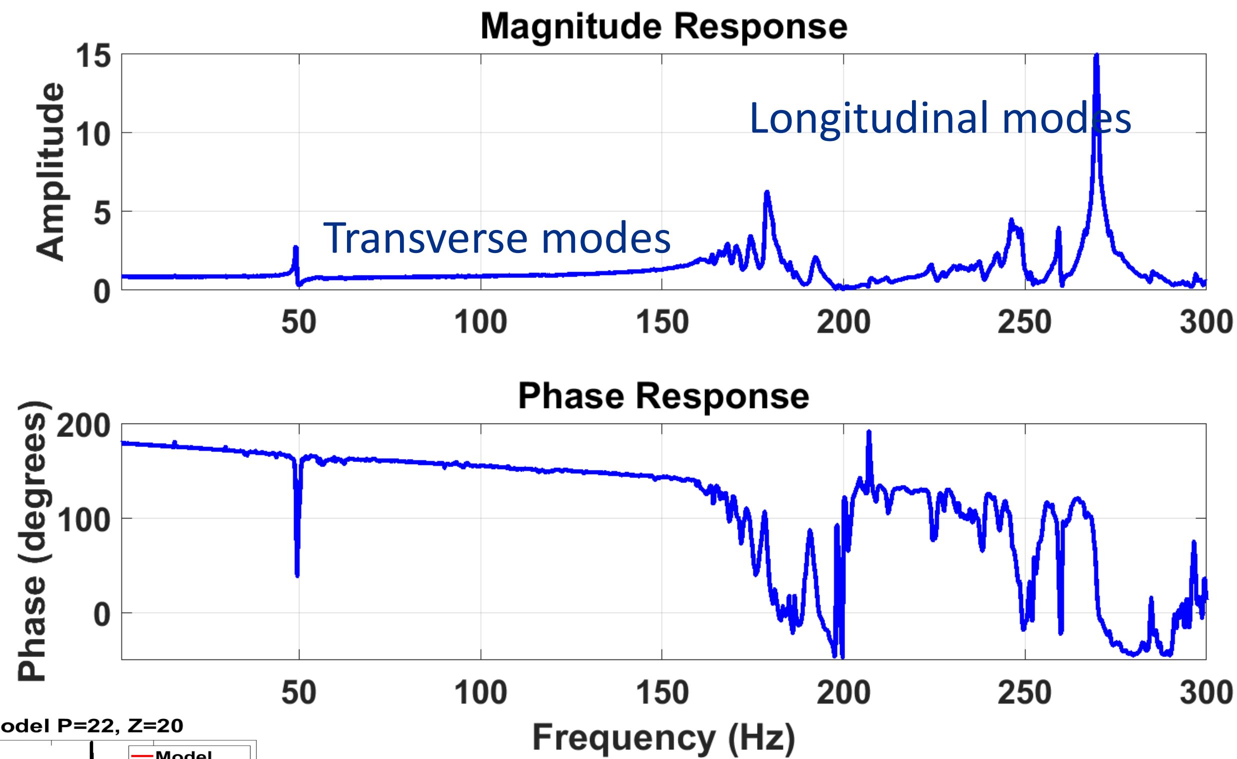
where $E_{p,q}$ is the $p \times q$ block matrix $[\, I_p \ \ 0_{p,q-p} \,]$.

Fermilab
PIP-II
Proton Improvement Plan-II

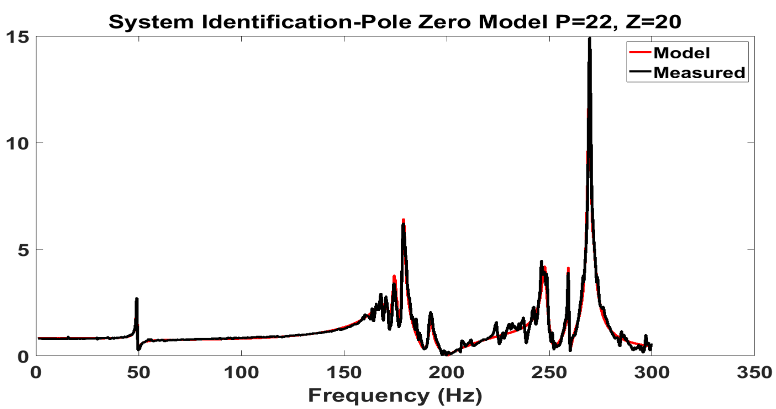
LCLS-II Transfer Function 0.25 Hz steps, 4 sec DAQ per point, 5 sec dwell

Charge #1

Extremely well behaved out to 175 Hz



0.66 millisecond group delay probably from DAQ



Process:

System identification

Internal Model Controler

Fermilab
PIP-II
Proton Improvement Plan-II

ESH&Q

Charge #6

- We follow Project ESH Management Plan, docdb #141 and Project QA plan docdb #142
- Almost all of the hazards associated with these systems are electrical in nature and are covered under the codes below listed in the PHAR (docdb# 140):
  - National Electrical Code, NFPA 70
  - OSHA 29 CFR, Part 1910, Subpart S, Electrical
  - Fermilab ESH&Q Manual, Fermilab Electrical Safety Program
- Domestically procured electrical equipment will be National Recognized Testing Lab (NRTL) certified.
- No exposed energy sources above 50V
- QC of deliverables –
  - Vendors follow IPC-A-610 rev. E, JSTD-001 rev. E, UL-60950
  - Visual inspection and 100% verification of modules meeting pre-established specifications

Development Oversight

Charge #6

- IIFC - Basic engineering oversight is accomplished though weekly collaboration meetings with presentations and review, and also through direct oversight by assigned engineers
  - Process follows the FNAL Engineering Manual
    - FRS, TRS, BOEs are complete or close to it
- QA/QC
  - Workmanship: IPC-A-610E (under discussion)
  - ROHS Compliant
  - Primary QA/QC of board level components will be in the hands of the assembly house. Documentation will be provided to Fermilab

Validation at Fermilab

Charge #6

- Hardware - Visual inspection and 100% testing and burn in will be done at Fermilab
- Software/Firmware – Modular design, full simulation and unit test
  - Requires full access to code and documentation in the software repository
- Controls interface – Co-developed at Fermilab with LLRF and Controls Department
- Tests with beam at PIP2IT
  - The current plan allows for six months of beam operations
  - Test stand installations will allow for system testing but without beam

Risk Management: LLRF

Charge #2,7

- Resonance control and field regulation
  - Since CD1 SRF cavities will operate in CW to mitigate LFD risk for resonance control
- Incompatibility in high performance electronic systems
- RF Interlocks fail to protect SSA-coupler-cavity

Edit	RI-ID	Title	Probability	Cost Impact	Schedule Impact	P * Impact (k$)	P * Impact (months)	Warnings	Comments	Risk Status
	RT-121-03-006	Incompatability in high performance electronic systems	25 %	100 -- 1500 k$	6 -- 12 months	200	2.3			Open
	RT-121-03-001	Resonance control and field regulation do not meet requirements	10 %	100 -- 3000 k$	2 -- 24 months	155	1.3		Consider having high schedule/cost impacts vs low schedule/cost impacts and	Open
	RT-121-03-017	RF interlocks fail to protect SSA-Coupler-Cavity	10 %	90 -- 250 -- 340 k$	2 -- 5 months	23	0.4	Schedule impact function has wrong number of arguments.		Open

Mitigation plan is in the RLS - Testing of complete systems at PIP2 IT and the test stands

Summary

- The LLRF team has good SRF experience, most recently with LCLS-II. The requirements for the PIP-II LLRF system are understood and our design is on-track to meet these requirements.
- The design is modular allowing short lifetime electronics reworks with minimal system impact
- Risks are understood although we have limited experience yet with any of five SRF cryomodule types and expect new “features” will keep the work interesting
- ESH and QA plans are in place
- LLRF is ontrack for CD-2 and we look forward to your feedback
- Thank you for your attention!