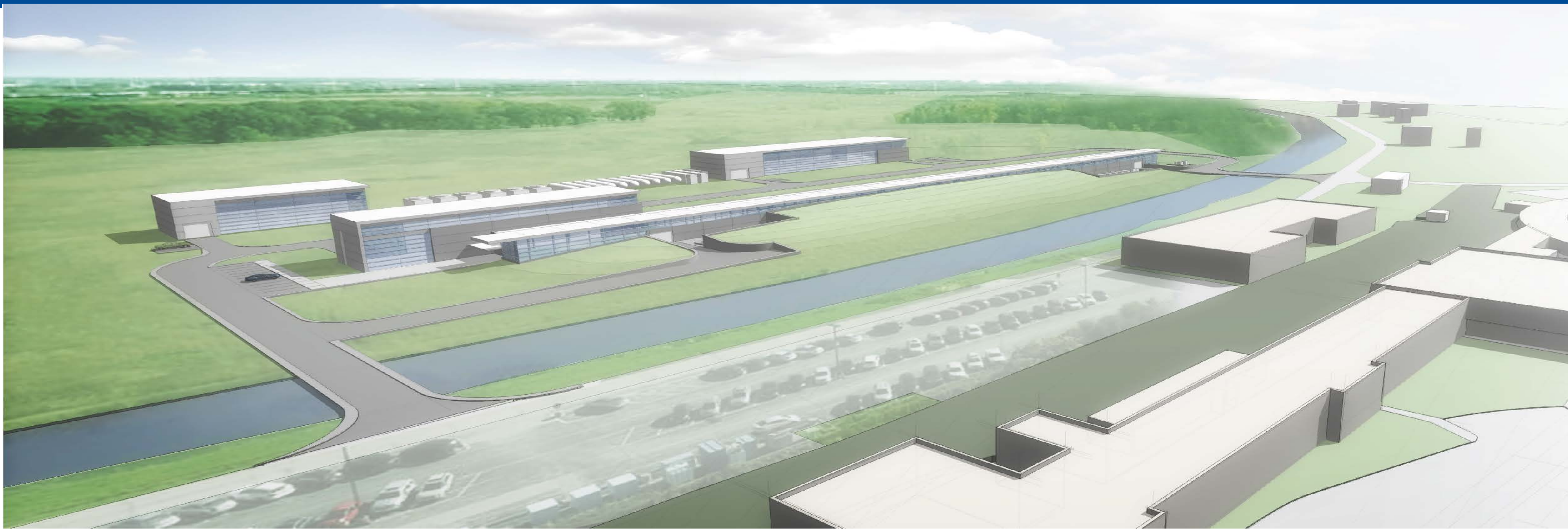


131.3.10 RF Integration

RF Systems, Controls, and Instrumentation

Brian Chase

PIP-II Director's Review

10-12 October 2017

In partnership with:
India Institutes Fermilab Collaboration
Istituto Nazionale di Fisica Nucleare
Science and Technology Facilities Council

Outline

- Requirements
- Conceptual Design, Maturity
- Scope/Deliverables
- Interfaces
- Technical Progress to Date
- ESH&Q
- Risk
- Cost
- Schedule
- Summary

About Me:

- Brian Chase:
  - L3 Manager for RF Integration
- Relevant experience
  - 30+ years in accelerator technology development
  - 400 MeV Linac, Main Injector, Tevatron, Recycler, SRF(A0, NML, ILC, LCLS-II)
  - Low Level RF group leader with an experienced team

WBS L3 System Requirements

Charge #1

- 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 system that supports pulsed or CW modes

- Chopper Driver: Beam pattern generator control
  - Provide signals necessary 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

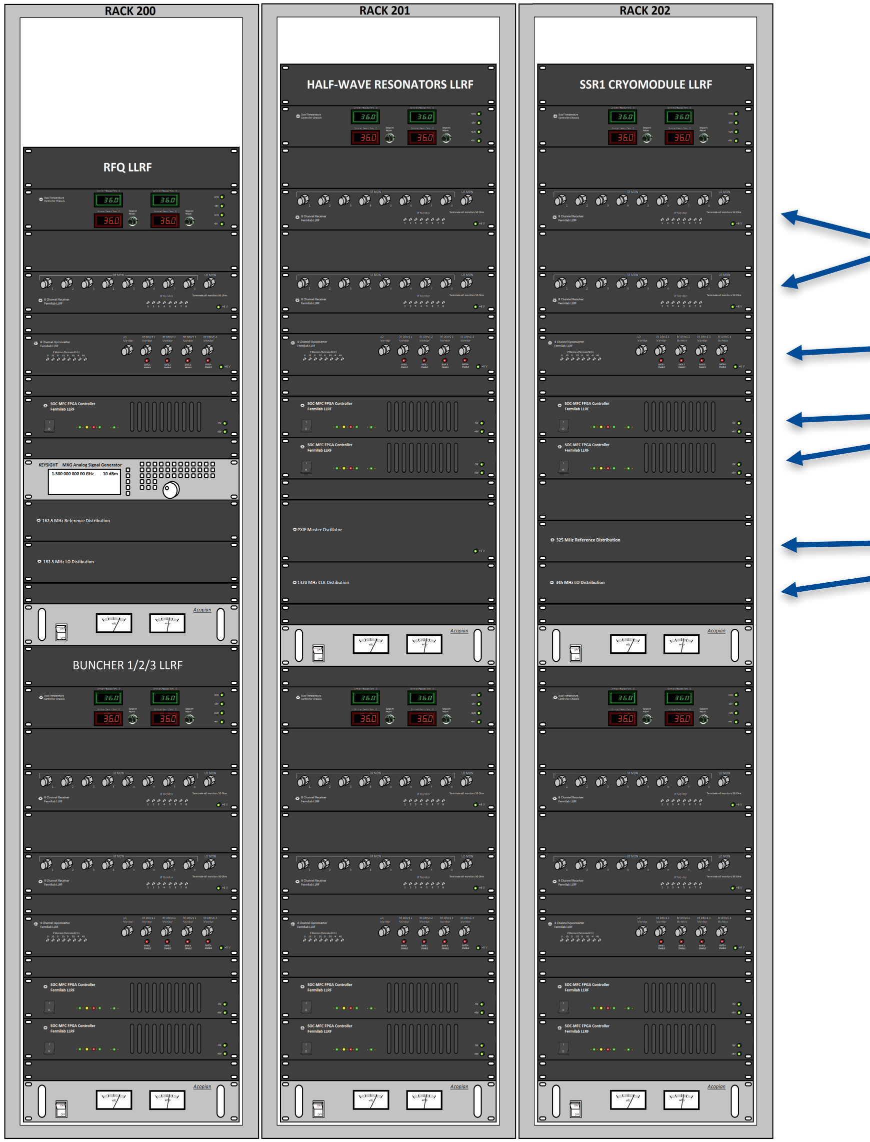
- All Systems provide diagnostic waveforms through the control system and interface with the Machine Protection System (MPS)

Conceptual Design and Design Maturity

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

- LLRF hardware is compatible for all frequencies and is repeated in racks controlling four cavities
- Each cavity frequency has its own Phase Reference Line and Local Oscillator
- RFPI supports all cavity types

LLRF Rack layout for PIP-II Front-end



(2) 8 Chanel Receivers

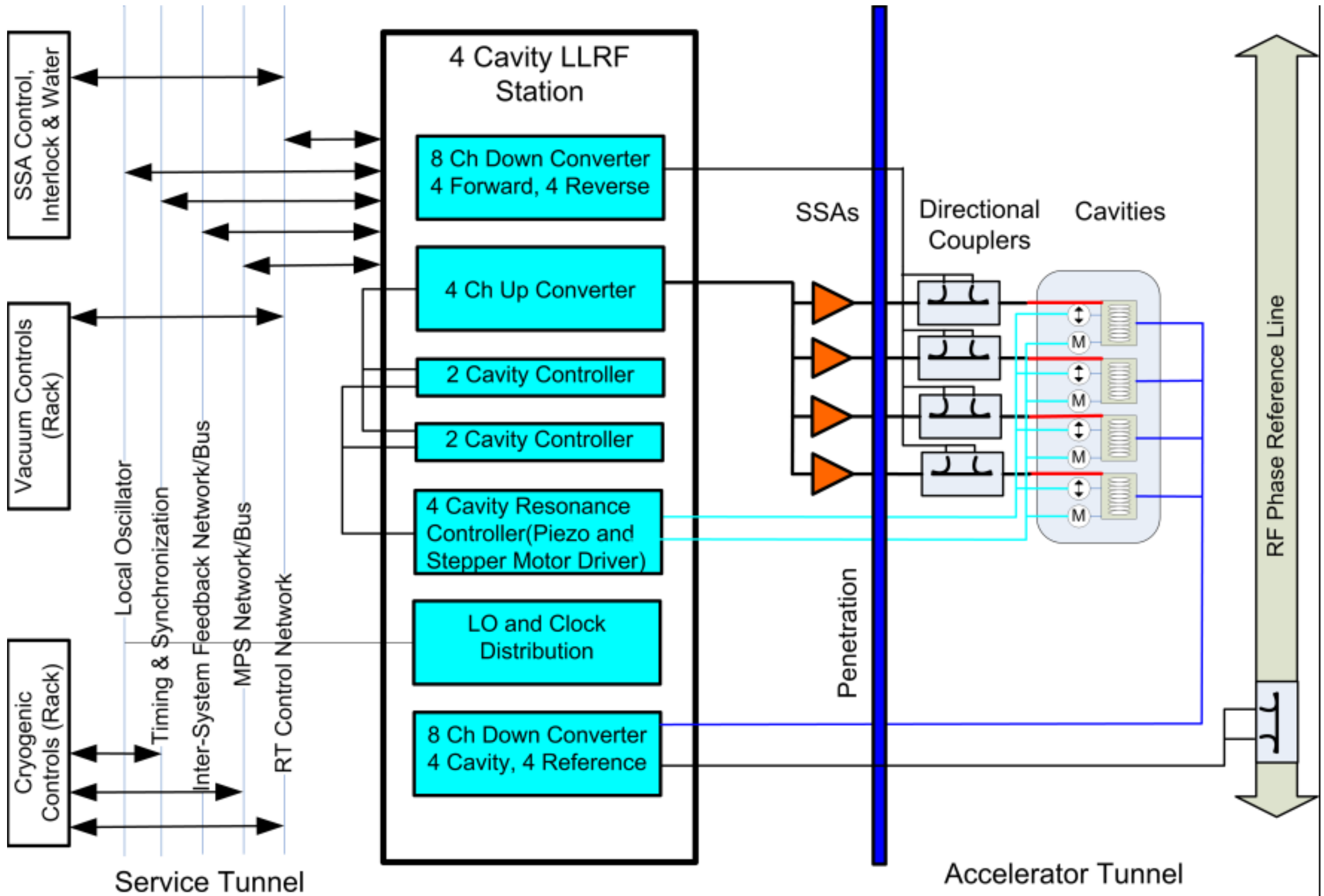
4 Chanel Up-converter

(2) 2 Chanel Controllers

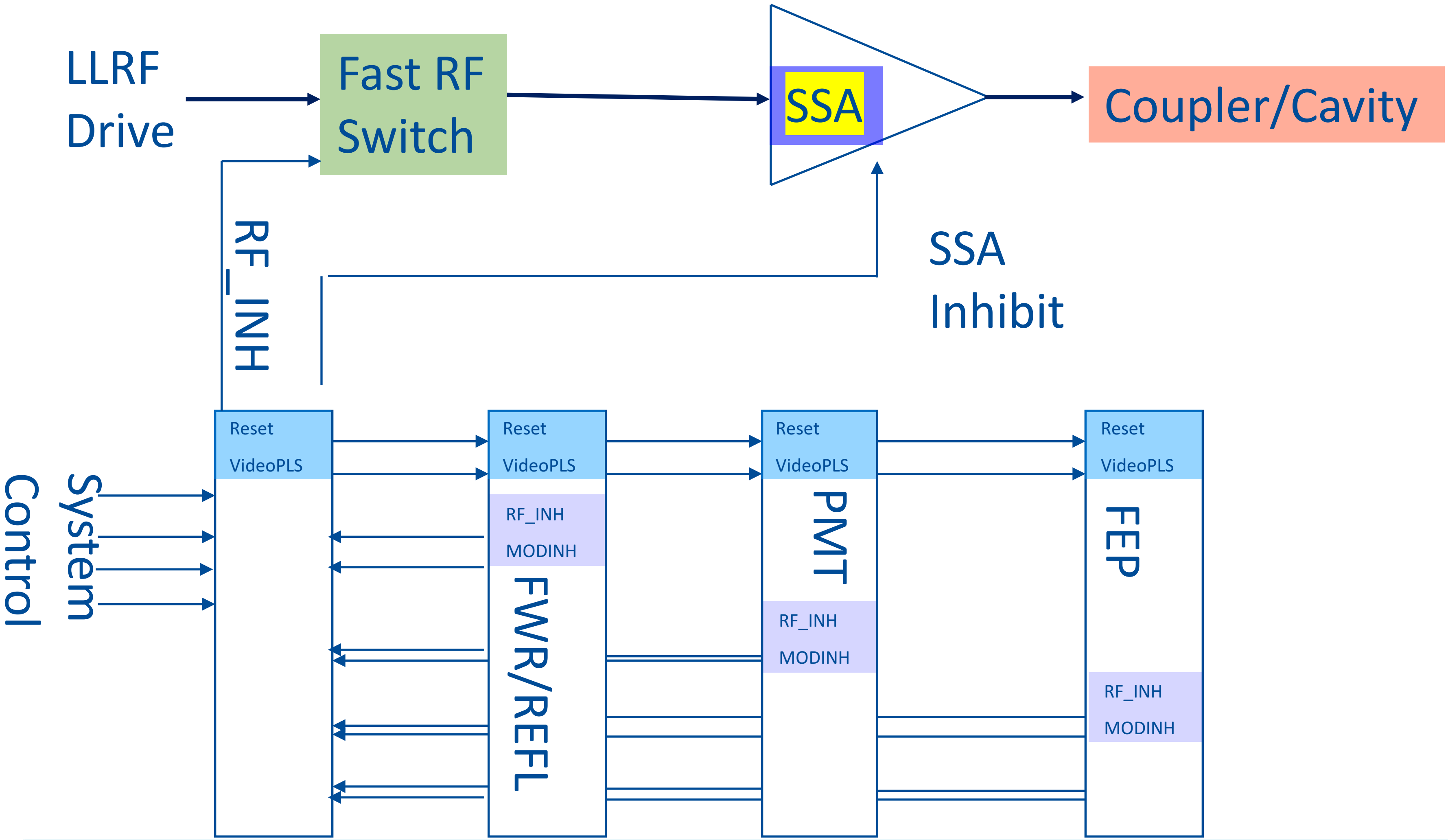
LO and Ref Distribution

Conceptual Design and Design Maturity: LLRF

Charge #1



Conceptual Design and Design Maturity: RFPI



Scope and Deliverables

Charge #1

- *Provide hardware, software, and firmware to satisfy system requirements.*

Scope and Deliverables

Charge #1

- *Provide hardware, software, and firmware to satisfy system requirements.*
- *PIP2-IT/CMTS LLRF:*
  - Low level RF for all cavities in each test stand
    - Systems for 162.5 MHz cavities is initially supplied by FNAL: DAE/BARC hardware will be integrated
    - All other hardware supplied by DAE/BARC
  - Resonance control for the RFQ and half wave resonators
  - Resonance control support for SSR and elliptical cavities

Scope and Deliverables

Charge #1

- *Provide hardware, software, and firmware to satisfy system requirements.*
- *PIP2-IT/CMTS LLRF:*
  - Low level RF for all cavities in each test stand
    - Systems for 162.5 MHz cavities is initially supplied by FNAL: DAE/BARC hardware will be integrated
    - All other hardware supplied by DAE /BARC
    - Resonance control for the RFQ and half wave resonators
  - Resonance control support for SSR and elliptical cavities
- *PIP-II LLRF Hardware Deliverables:*
  - 8 Channel down-converter (DAE/BARC deliverable)
  - 4 Channel up-converter (DAE/BARC deliverable)
  - Rack power supplies (DAE/BARC deliverable)
  - Resonance control chassis (IIFC deliverable)
  - Field control chassis (DAE/BARC deliverable)
  - Reference line system
  - Chopper pattern generator

Scope and Deliverables

Charge #1

- *PIP-II LLRF Software/Firmware Deliverables:*
  - Data acquisition firmware (DAE/BARC Deliverable)
  - Field control firmware (DAE/BARC Deliverable)
  - Resonance control integration
  - Software (DAE/BARC Deliverable)
  - Global system control
  - Chopper Waveform Generator
  - Beam-based energy stabilization

Scope and Deliverables

Charge #1

- *PIP-II LLRF Software/Firmware Deliverables:*
  - Data acquisition firmware (IIFC Deliverable)
  - Field control firmware (IIFC Deliverable)
  - Resonance control integration
  - Software (IIFC Deliverable)
  - Global system control
  - Chopper Waveform Generator
  - Beam-based energy stabilization

- *RFPI Deliverables*
  - *PIP2-IT systems*
  - *CMTS(IIFC Deliverable)*
  - *PIP-II all SRF cavities Hardware/Software/Firmware(FNAL and IIFC Deliverable)*

Interfaces

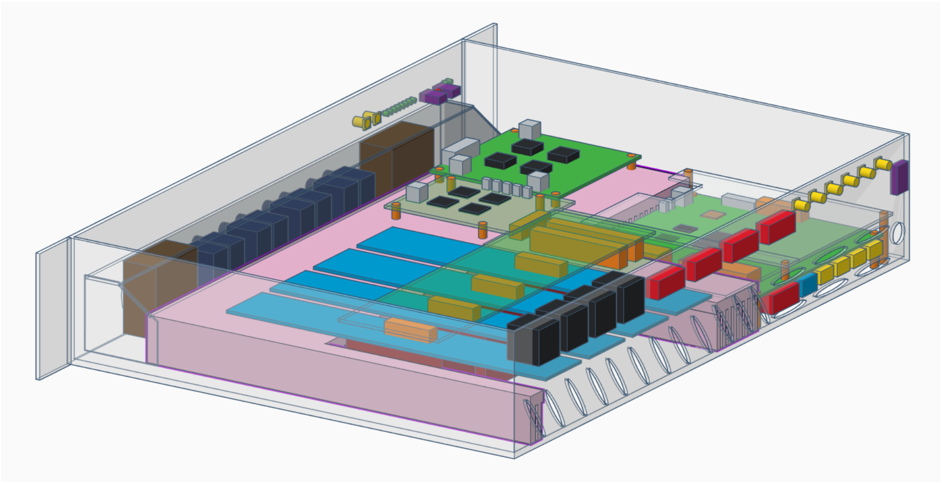
Charge #1

- *LLRF/RFPI:*
  - **High Level RF: (SSA, directional couplers)**
  - **Cryomodules: (coupler, cavity, vacuum)**
  - **Timing/events:**
  - **Machine protection system:**
  - **Controls:**
  - **Booster RF:**
  - **Instrumentation**
    - **Global energy stabilization:**

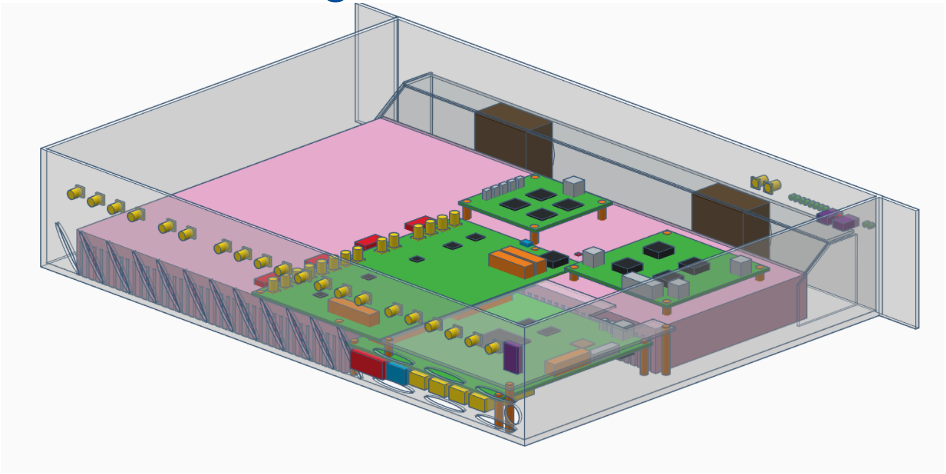
Progress to date: LLRF Systems and Chassis layout

- Seven joint FRSs Approved (two more near approval)
  - TRS 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 layout
- ADC-DAC FMC Module
  - Layout
- Resonance Control Chassis
  - Leverage from FNAL LCLS-II design and is in progress

Resonance Control Chassis

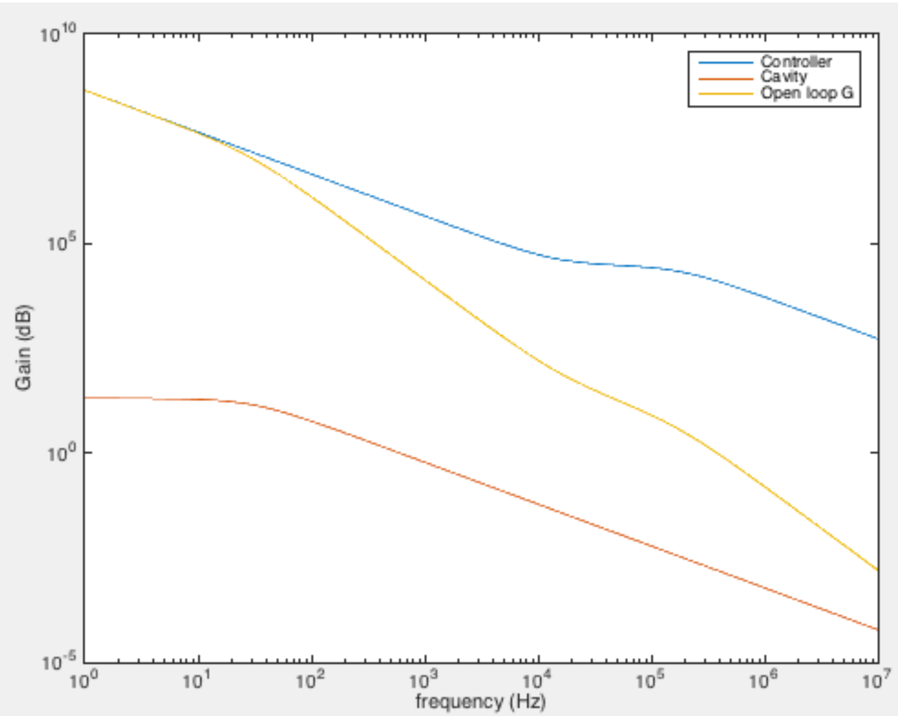


Digitizer Chassis

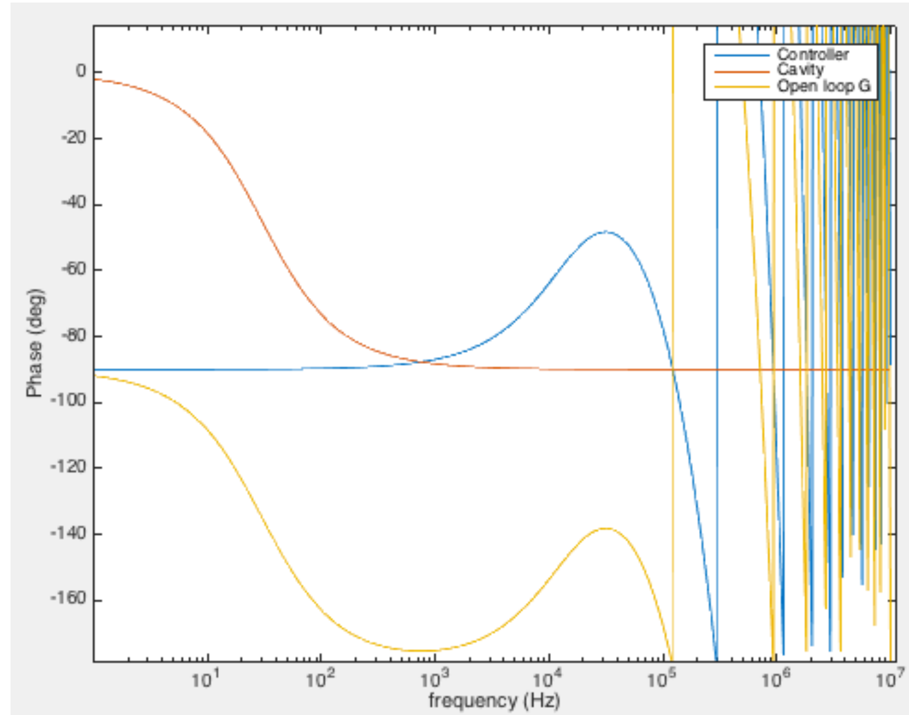


Progress to date: Open loop transfer function simulation of cavity and controller

Magnitude



Phase



Max gain

Closed-loop bandwidth: ~50 kHz

Control system zero: 15 kHz

Proportional gain: 1500

Integral gain: 1.44e+08

Nominal gain

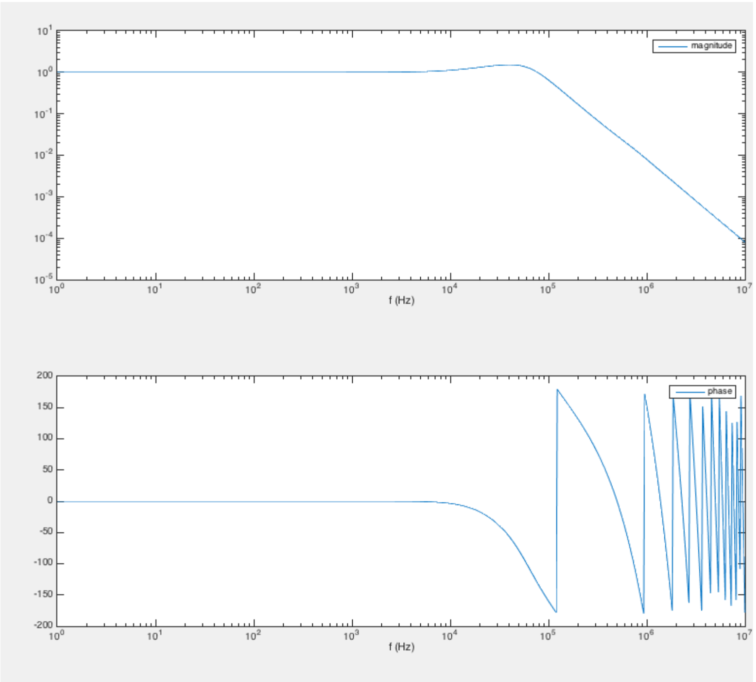
Closed-loop bandwidth: ~25 kHz

Proportional gain: 750

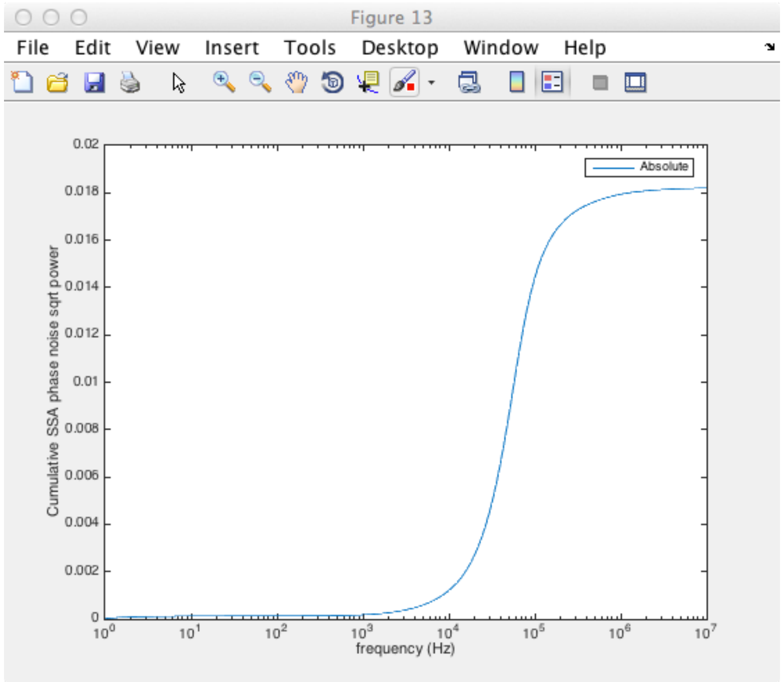
Integral gain: 7e+07

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

Closed loop response



Cumulative SSA phase noise voltage



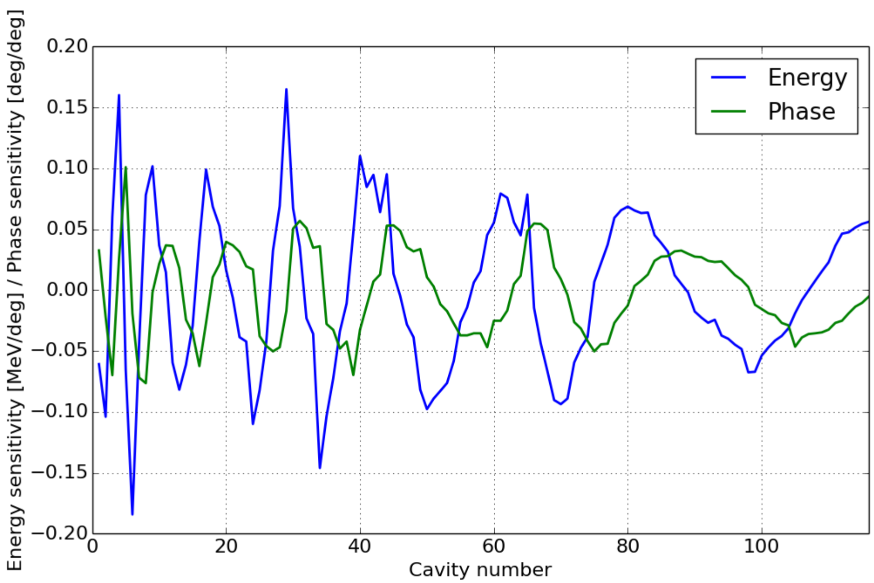
Careful attention to noise terms will allow high controller gains

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

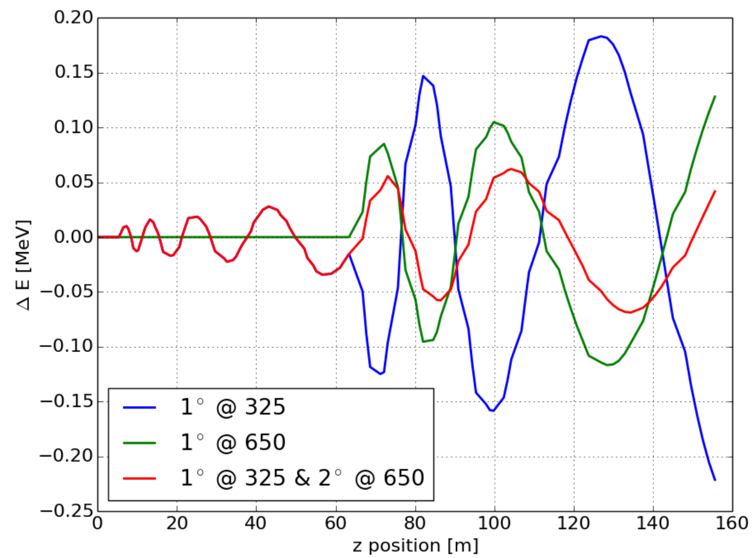
Code developed for LCLS-II
Larry Doolittle LBNL and FNAL

Progress to date: Phase-energy Stability Simulations

- 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

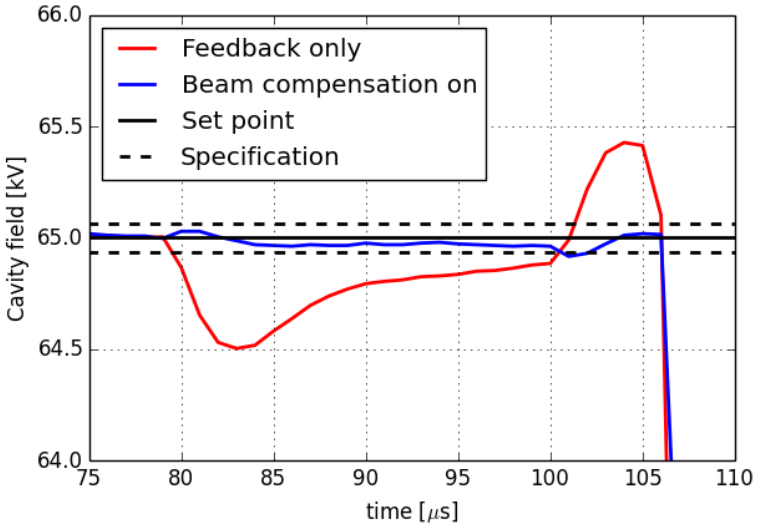


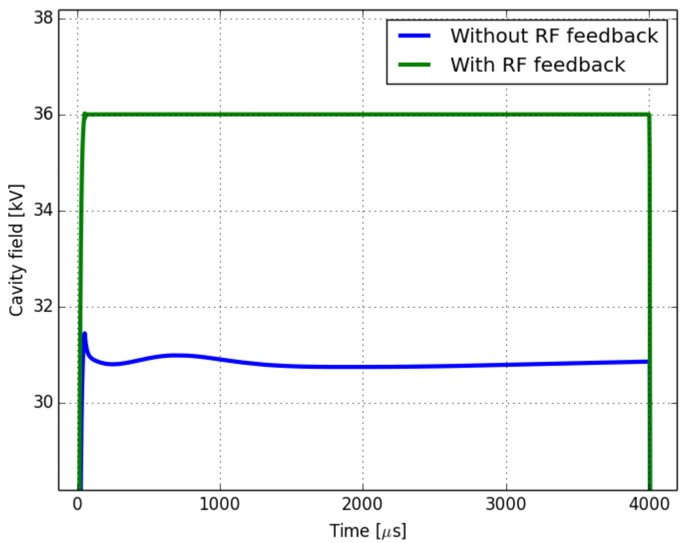
Linac output energy sensitivity to phase reference line phase errors at frequency transitions

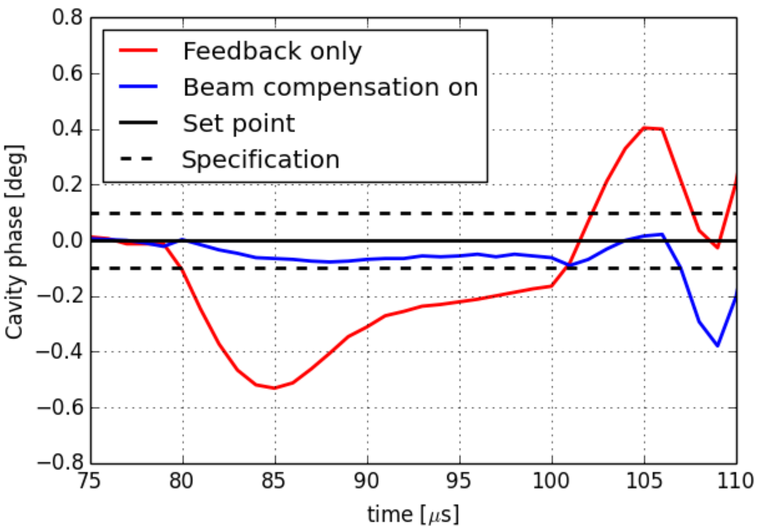
J. Edelen

Progress to date

- 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







Progress to date: RFPI

- RFPI Hardware Prototype Delivered by BARC

ESH&Q

Charge #4

- 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 IIFC deliverables - Visual inspection and 100% verification of modules meeting pre-established specifications

Risk: RF Integration

- Resonance control and field regulation
- Incompatibility in high performance electronic systems
- IIFC LLRF hardware/software does not meet acceptance criteria

Title	Probability	Probability Score	P * Impact (k$)	P * Impact (months)	Impact Score - Cost	Impact Score - Schedule	Risk Rank
Resonance control and field regulation	40.00%	4 (H)	700	6.0	2 (M)	3 (H)	3 (High)
Incompatability in high performance electronic systems	60.00%	4 (H)	630	9.0	2 (M)	3 (H)	3 (High)
IIFC LLRF hardware/software does not meet acceptance criteria	50.00%	4 (H)	400	3.8	2 (M)	3 (H)	3 (High)

BOE Summary

Charge #2

WBS Number	Title	Docdb #
121.3.10.2	Linac – RF-INT Project Management and Coordination	
121.3.10.3.1	Linac – RF-INT – LLRF PIP2IT	
121.3.10.3.2	Linac – RF-INT – LLRF Test Infrastructure	
121.3.10.3.3	Linac – RF-INT – LLRF PIP-II	
121.3.10.4	Linac – RF-INT Reference Line (RL)	
121.3.10.5	Linac – RF-INT – RFPI	

Cost Summary

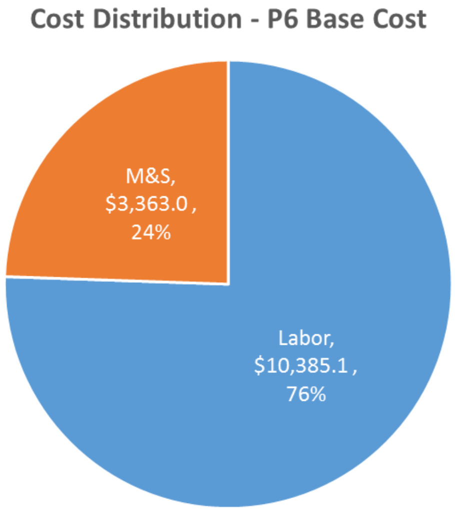
Charge #2

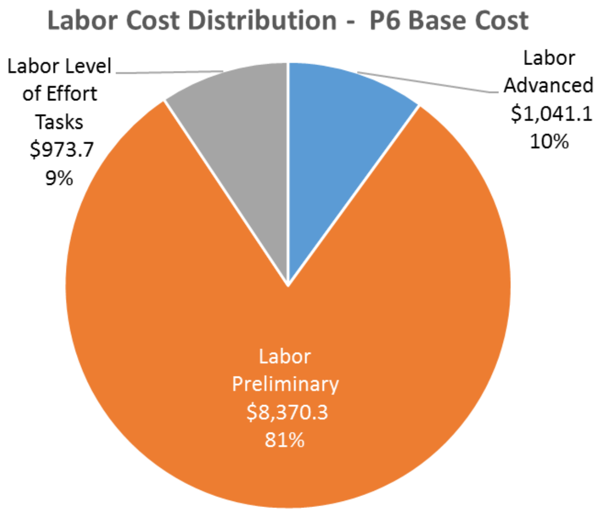
WBS Element	Hours	Labor ($000)	M&S ($000)	Est. Uncertainty ($000)		
121.3.10 - Linac - RF power INTegration (RF-INT)	P6 Hours	P6 Base Cost	P6 Base Cost	Total	% of Base	Total Cost Incl. Uncrty.
121.3.10.2 - Linac - RF-INT - Project Management and Coordination	6,126	$ 973.7	$ 69.6	$ 212.1	20.3%	$ 1,255.4
121.3.10.3 - Linac - RF-INT - Low Level Radio Frequency (LLRF)	42,138	$ 6,150.6	$ 1,828.5	$ 2,471.7	31.0%	$ 10,450.9
121.3.10.4 - Linac - RF-INT - Reference Line (RefL)	4,881	$ 659.4	$ 358.8	$ 305.5	30.0%	$ 1,323.7
121.3.10.5 - Linac - RF-INT - InterLocks (IntL)	18,850	$ 2,601.4	$ 1,106.0	$ 1,040.7	28.1%	$ 4,748.1
Grand Total	**71,995**	**$ 10,385.1**	**$ 3,363.0**	**$ 4,030.0**	**29.3%**	**$ 17,778.1**
Note: P6 base cost = BOE + overheads and escalation						

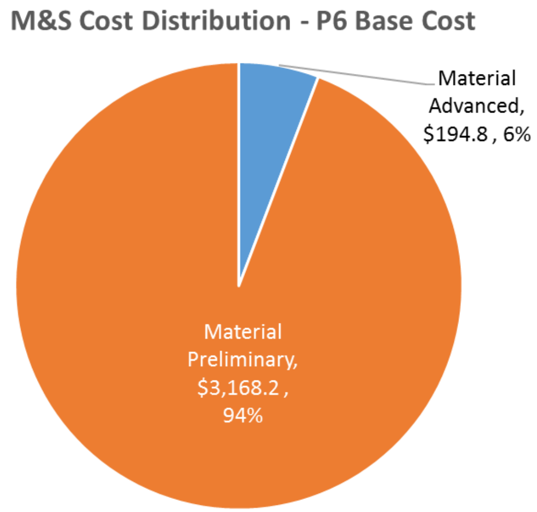
- 121.3.10.3 includes PIP2-IT, Resonance control and PIP-II

Cost Drivers and Estimate Maturity

Charge #2





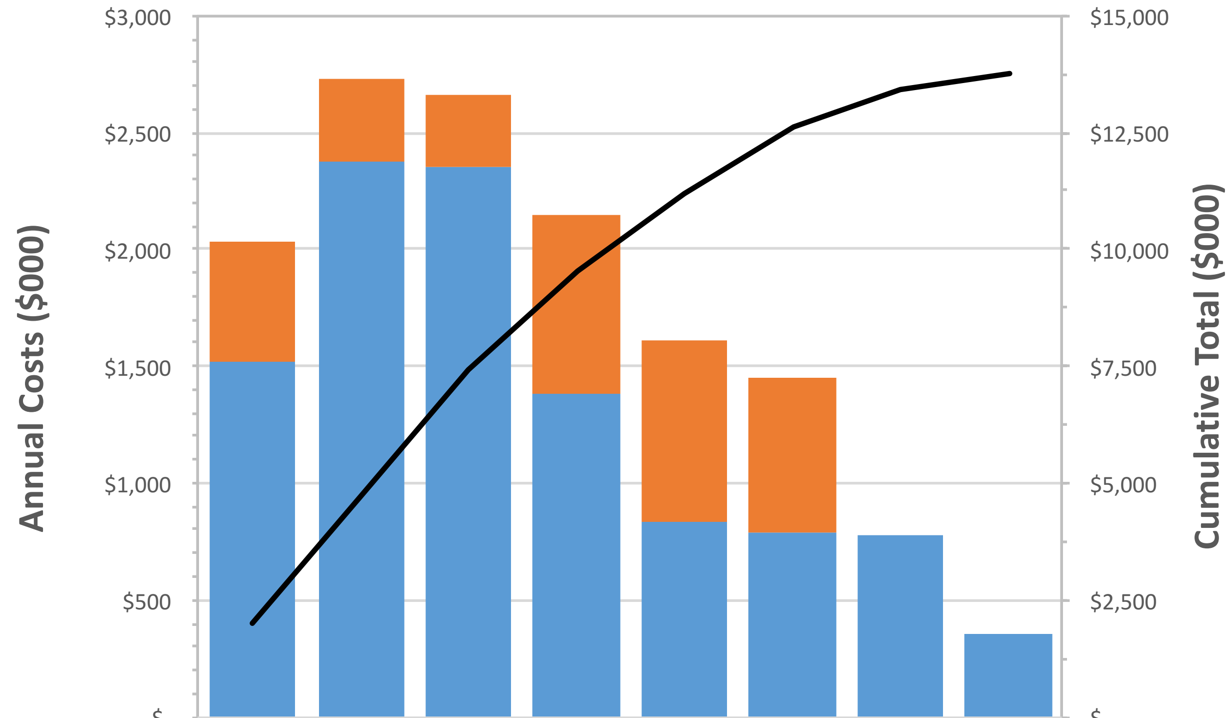


P6 Base Costs = BOE + Overheads + Escalation

M&S is covered in part by IIFC

Cost Profile – P6 Base Cost Only

Charge #2



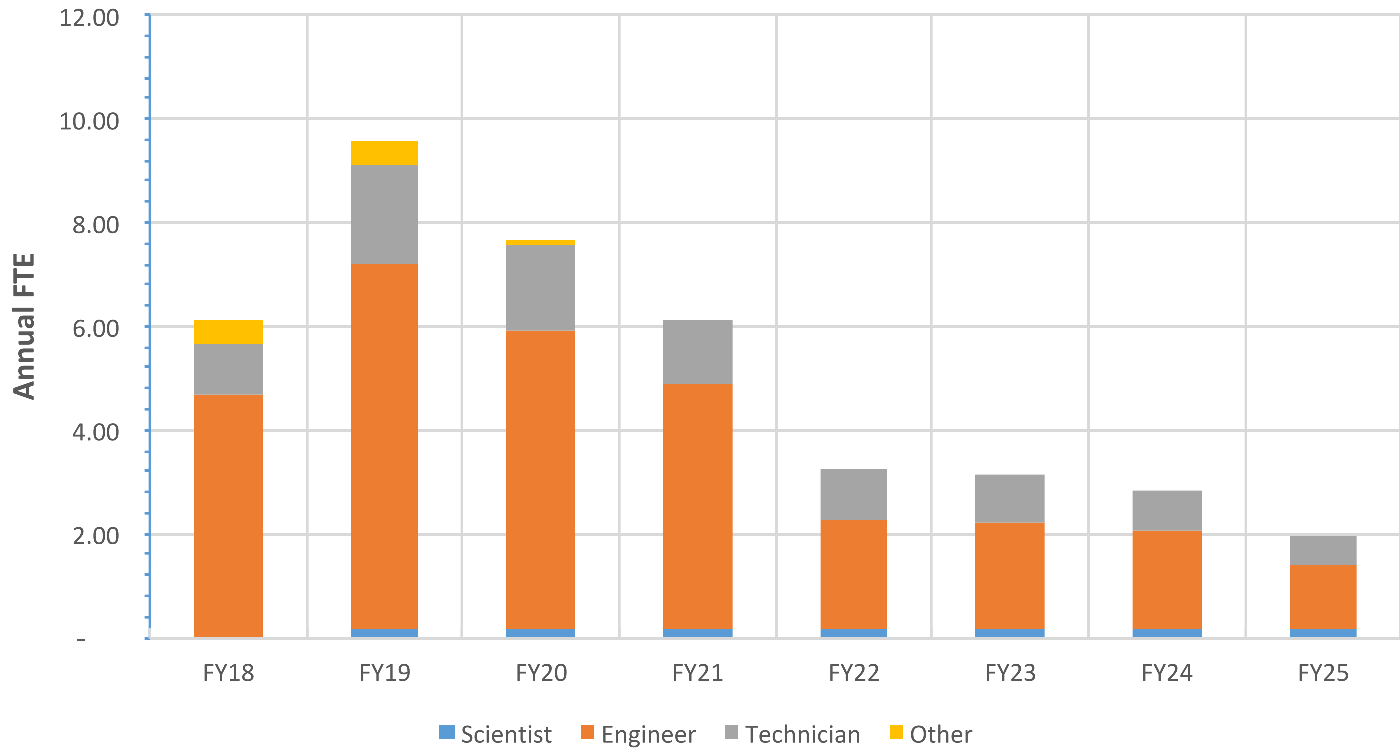
	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25
Material	$508.6	$346.4	$309.7	$758.3	$779.1	$660.9	$-	$-
Labor	$1,519.6	$2,378.1	$2,350.5	$1,386.5	$837.0	$785.2	$776.7	$351.4
Cumulative Tot.	$2,028.2	$4,752.7	$7,413.0	$9,557.8	$11,173.	$12,620.	$13,396.	$13,748.

P6 Base Costs = BOE + Overheads + Escalation

FY19 and FY20 bump to finish R&D in time to meet IIFC schedule

Labor Profile – P6 Hours/FTE

Charge #2

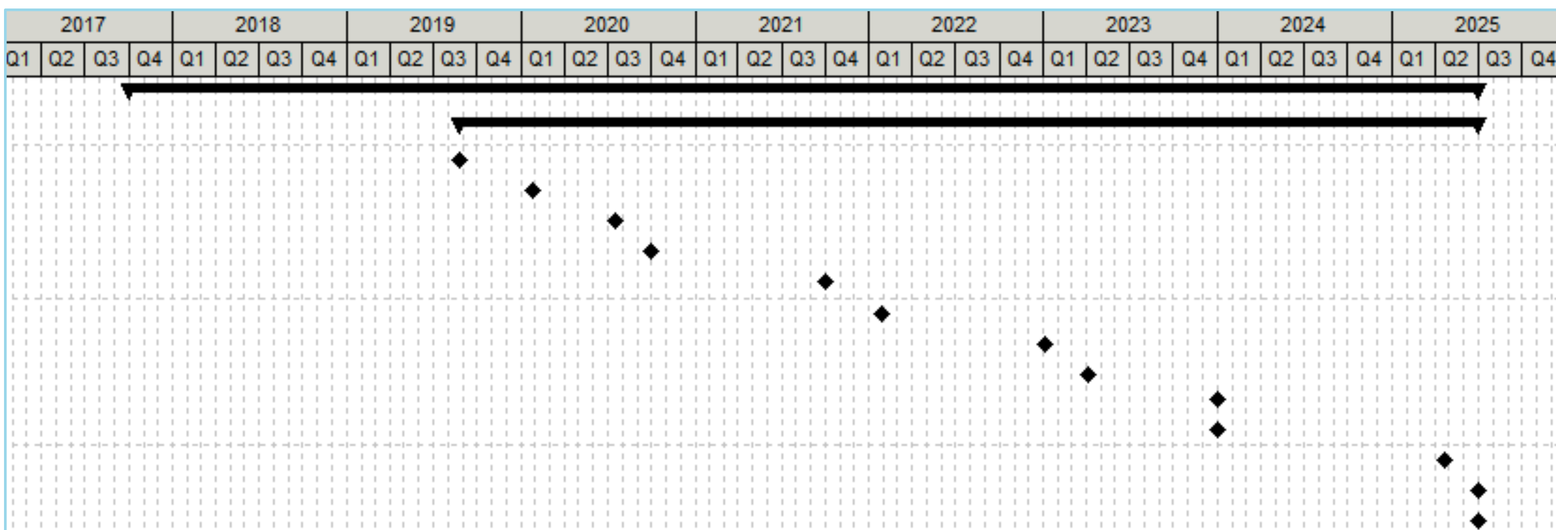


FY19 and FY20 bump to finish R&D in time to meet IIFC schedule

Schedule – RF power Integration

Charge #2

Activity ID	Activity Name
121.3.10 Linac - RF power INTegration (RF-INT)	
121.3.10.1 Linac - RF-INT - T4 Milestones	
A17750840	Linac - RF-INT - IntL - PIP2IT - R&DPh: T4 MS - SSR1 Interlocks System Commissioned before starting SSR1 RF Test
A17750830	Linac - RF-INT - IntL - PIP2IT - R&DPh: T4 MS - HWR Interlocks System Commissioned before starting HWR RF Test
A17733760	Linac - RF-INT - LLRF - PIP2IT - R&DPh: T4 MS - SSR1 LLRF System Commissioned (3m after start RF Test for SSR1)
A17733750	Linac - RF-INT - LLRF - PIP2IT - R&DPh: T4 MS - HWR LLRF System Commissioned (3m after start RF Test for HWR)
A17733770	Linac - RF-INT - LLRF - PIP2IT - R&DPh: T4 MS - 20 Hz Resonance Control Demostrated (1 year after LLRF commissioned)
A17733780	Linac - RF-INT - LLRF - TI - R&DPh: T4 MS - CMTS LLRF System Commissioned
A17750790	Linac - RF-INT - LLRF - PIP-II - ConstrPh: T4 MS - LLRF Stations Ready For Installation in High Bay for WFE
A17750820	Linac - RF-INT - RefL - PIP-II - ConstrPh: T4 MS - RF Reference Line Ready For Installation
A17750800	Linac - RF-INT - LLRF - PIP-II - ConstrPh: T4 MS - LLRF Stations Ready For Installation in Linac Gallery for SRF
A17750850	Linac - RF-INT - IntL - PIP-II - ConstrPh: T4 MS - Linac SRF Interlocks System Ready For Installation
A17733790	Linac - RF-INT - LLRF - TI - ConstrPh: T4 MS - 20 Hz Resonance Control Demostarted for 650 MHz
A17750810	Linac - RF-INT - LLRF - PIP-II - ConstrPh: T4 MS - LLRF Stations in the Gallery ready for integration
A17750860	Linac - RF-INT - IntL - PIP-II - ConstrPh: T4 MS - Interlocks Stations in the Gallery ready for integration



PIP-II

Summary

- The Low Level RF and RF protection and interlock are leveraged from FNAL and LCLS-II designs and well understood
- The beam energy stability requirements are very tight for a pulsed machine, however, full machine simulations and testing at PIP2-IT show them to be attainable
- There is ongoing work and a plan forward to cover Lorentz force detuning (resonance control)
- We have a good working relationship with our DAE collaborators
- Cost, schedule and risks are understood
- We are ready for CD-1 and look forward to your feedback

Thank you for your attention!