131.3.10 RF Integration

RF Systems, Controls, and Instrumentation

Brian Chase
PIP-II Director’s Review
10-12 October 2017
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

• 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**

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>Number of RF cavities</th>
<th>Amplifiers per Cavity</th>
<th>Pulsed / CW</th>
<th>Amplifier power [kW]</th>
<th>Number of 4-cavity stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFQ</td>
<td>162.5</td>
<td>1</td>
<td>2</td>
<td>CW</td>
<td>75</td>
</tr>
<tr>
<td>Bunching Cavities</td>
<td>162.5</td>
<td>4</td>
<td>1</td>
<td>CW</td>
<td>3</td>
</tr>
<tr>
<td>HWRs</td>
<td>162.5</td>
<td>8</td>
<td>1</td>
<td>CW</td>
<td>3,7</td>
</tr>
<tr>
<td>SSR1s</td>
<td>325</td>
<td>16</td>
<td>1</td>
<td>Pulsed</td>
<td>7</td>
</tr>
<tr>
<td>SSR2s</td>
<td>325</td>
<td>35</td>
<td>1</td>
<td>Pulsed</td>
<td>20</td>
</tr>
<tr>
<td>LB650s</td>
<td>650</td>
<td>33</td>
<td>1</td>
<td>Pulsed</td>
<td>40</td>
</tr>
<tr>
<td>HB650s</td>
<td>650</td>
<td>24</td>
<td>1</td>
<td>Pulsed</td>
<td>70</td>
</tr>
</tbody>
</table>

- 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.
(2) 8 Channel Receivers

4 Channel Up-converter

(2) 2 Channel Controllers

LO and Ref Distribution
Conceptual Design and Design Maturity: LLRF

Charge #1
Conceptual Design and Design Maturity: RFPI
Scope and Deliverables

• *Provide hardware, software, and firmware to satisfy system requirements.*
Scope and Deliverables

- 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

- **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

• 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

• **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

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

Magnitude

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

- 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

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance control and field regulation</td>
<td>40.00%</td>
<td>4 (H)</td>
<td>700</td>
<td>6.0</td>
<td>2 (M)</td>
<td>3 (H)</td>
<td>3 (High)</td>
</tr>
<tr>
<td>Incompatibility in high performance electronic systems</td>
<td>60.00%</td>
<td>4 (H)</td>
<td>630</td>
<td>9.0</td>
<td>2 (M)</td>
<td>3 (H)</td>
<td>3 (High)</td>
</tr>
<tr>
<td>IIFC LLRF hardware/software does not meet acceptance criteria</td>
<td>50.00%</td>
<td>4 (H)</td>
<td>400</td>
<td>3.8</td>
<td>2 (M)</td>
<td>3 (H)</td>
<td>3 (High)</td>
</tr>
</tbody>
</table>
## BOE Summary

<table>
<thead>
<tr>
<th>WBS Number</th>
<th>Title</th>
<th>Docdb #</th>
</tr>
</thead>
<tbody>
<tr>
<td>121.3.10.2</td>
<td>Linac – RF-INT Project Management and Coordination</td>
<td></td>
</tr>
<tr>
<td>121.3.10.3.1</td>
<td>Linac – RF-INT – LLRF PIP2IT</td>
<td></td>
</tr>
<tr>
<td>121.3.10.3.2</td>
<td>Linac – RF-INT – LLRF Test Infrastructure</td>
<td></td>
</tr>
<tr>
<td>121.3.10.3.3</td>
<td>Linac – RF-INT – LLRF PIP-II</td>
<td></td>
</tr>
<tr>
<td>121.3.10.4</td>
<td>Linac – RF-INT Reference Line (RL)</td>
<td></td>
</tr>
<tr>
<td>121.3.10.5</td>
<td>Linac – RF-INT – RFPI</td>
<td></td>
</tr>
</tbody>
</table>
### Cost Summary

<table>
<thead>
<tr>
<th>WBS Element</th>
<th>Hours</th>
<th>Labor ($000)</th>
<th>M&amp;S ($000)</th>
<th>Est. Uncertainty ($000)</th>
<th>Total Cost Incl. Uncrty.</th>
</tr>
</thead>
<tbody>
<tr>
<td>121.3.10 - Linac - RF power INTegration (RF-INT)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>121.3.10.2 - Linac - RF-INT - Project Management and Coordination</td>
<td>6,126</td>
<td>$ 973.7</td>
<td>$ 69.6</td>
<td>$ 212.1</td>
<td>20.3%</td>
</tr>
<tr>
<td>121.3.10.3 - Linac - RF-INT - Low Level Radio Frequency (LLRF)</td>
<td>42,138</td>
<td>$ 6,150.6</td>
<td>$ 1,828.5</td>
<td>$ 2,471.7</td>
<td>31.0%</td>
</tr>
<tr>
<td>121.3.10.4 - Linac - RF-INT - Reference Line (RefL)</td>
<td>4,881</td>
<td>$ 659.4</td>
<td>$ 358.8</td>
<td>$ 305.5</td>
<td>30.0%</td>
</tr>
<tr>
<td>121.3.10.5 - Linac - RF-INT - InterLocks (IntL)</td>
<td>18,850</td>
<td>$ 2,601.4</td>
<td>$ 1,106.0</td>
<td>$ 1,040.7</td>
<td>28.1%</td>
</tr>
<tr>
<td><strong>Grand Total</strong></td>
<td><strong>71,995</strong></td>
<td><strong>$ 10,385.1</strong></td>
<td><strong>$ 3,363.0</strong></td>
<td><strong>$ 4,030.0</strong></td>
<td><strong>29.3%</strong></td>
</tr>
</tbody>
</table>

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

P6 Base Costs = BOE + Overheads + Escalation

M&S Cost Distribution - P6 Base Cost
- Labor, $8,370.3, 81%
- Labor Advanced $1,041.1, 10%
- Material Advanced, $194.8, 6%

Labor Cost Distribution - P6 Base Cost
- Labor Level of Effort Tasks $973.7, 9%
- Labor Preliminary, $3,363.0, 24%
- Labor, $10,385.1, 76%

M&S is covered in part by IIFC
Cost Profile – P6 Base Cost Only

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

P6 Base Costs = BOE + Overheads + Escalation

FY19 and FY20 bump to finish R&D in time to meet IIFC schedule
FY19 and FY20 bump to finish R&D in time to meet IIFC schedule
Schedule – RF power Integration

<table>
<thead>
<tr>
<th>Activity ID</th>
<th>Activity Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>121.3.10Linac RF power INTEGRATION (RF-INT)</td>
<td>121.3.10.1Linac RF-INT - T4 Milestones</td>
</tr>
<tr>
<td>A17750840 Linac RF-INT INTL PIP2T R&amp;DPh T4 MS SSR1 Interlocks System Commissioned before starting SSR1 RF Test</td>
<td></td>
</tr>
<tr>
<td>A17750830 Linac RF-INT INTL PIP2T R&amp;DPh T4 MS HWR Interlocks System Commissioned before starting HWR RF Test</td>
<td></td>
</tr>
<tr>
<td>A17733760 Linac RF-INT LLRF PIP2T R&amp;DPh T4 MS SSR1 LLRF System Commissioned (3m after start RF Test for SSR1)</td>
<td></td>
</tr>
<tr>
<td>A17733750 Linac RF-INT LLRF PIP2T R&amp;DPh T4 MS HWR LLRF System Commissioned (3m after start RF Test for HWR)</td>
<td></td>
</tr>
<tr>
<td>A17733770 Linac RF-INT LLRF PIP2T R&amp;DPh T4 MS 20 Hz Resonance Control Demonstrated (1 year after LLRF commissioned)</td>
<td></td>
</tr>
<tr>
<td>A17733780 Linac RF-INT LLRF TI R&amp;DPh T4 MS CMTS LLRF System Commissioned</td>
<td></td>
</tr>
<tr>
<td>A17750790 Linac RF-INT LLRF PIP II ConstrPh T4 MS LLRF Stations Ready For Installation in High Bay for WFE</td>
<td></td>
</tr>
<tr>
<td>A17750820 Linac RF-INT Refl PIP II ConstrPh T4 MS RF Reference Line Ready For Installation</td>
<td></td>
</tr>
<tr>
<td>A17750800 Linac RF-INT LLRF PIP II ConstrPh T4 MS LLRF Stations Ready For Installation in Linac Gallery for SRF</td>
<td></td>
</tr>
<tr>
<td>A17750850 Linac RF-INT IntL PIP II ConstrPh T4 MS Linac SRF Interlocks System Ready For Installation</td>
<td></td>
</tr>
<tr>
<td>A17733790 Linac RF-INT LLRF TI ConstrPh T4 MS 20 Hz Resonance Control Demostarted for 650 MHz</td>
<td></td>
</tr>
<tr>
<td>A17750810 Linac RF-INT LLRF PIP II ConstrPh T4 MS LLRF Stations in the Gallery ready for integration</td>
<td></td>
</tr>
<tr>
<td>A17750860 Linac RF-INT IntL PIP II ConstrPh T4 MS Interlocks Stations in the Gallery ready for integration</td>
<td></td>
</tr>
</tbody>
</table>
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!