WBS 121.3.11 Cryogenics
SC Acceleration Modules and Cryogenics
Anindya Chakravarty and Arkadiy Klebaner
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

• System overview
• About Me
• Performance Requirements
• Conceptual Design, Maturity
• Scope/Deliverables
• Interfaces
• Organization
• Technical Progress to Date/Design Review Plan
• ESH&Q
• Cost
• Risk
• Schedule
• Summary
About Me:

• Role in PIP-II: Scientist
  - Superfluid Helium Cryogenic Plant and associated systems

• Relevant experience:
  - SO-G, CrTD, BARC (current position)
  - Group Leader, CrTD, BARC
  - Development of helium liquefaction and refrigeration systems at BARC
  - Development of cryogenic turboexpanders at BARC
  - Ph. D. in Cryogenic Engineering
System Overview

- Fully segmented Linac
- Single cold box with turbines and cold compressors
- Distribution box located in the refrigerator room
- Cryogenic transferline with bayonet cans that runs parallel to the cryomodules
WBS 121.11.3 Requirements flow down

**PIP-II Conceptual Design Report**

- Cryomodules requirement documents
  - TC#ED0001313, TC#ED0001316, TC#ED0001829, TC#ED0001830, TC#ED0001322

- **Cryogenic System**
  - Functional Requirements Specifications (TC#ED0003531)
  - Engineering Specifications (TC#ED0005493, 5587, etc.)
  - Design Criteria Documents (TC#ED0004748, 6895, etc.)
  - Engineering Notes (TC#ED0003531, 6860, 6901, etc.)
  - Interface Control Documents (TC#ED0006893)
Key Requirements

- *Project Key Performance Parameters* and *Physics Requirements* shall be met

- Linac operating modes:
  - CW or pulsed mode
  - 2.0 K in the standby mode
  - 4.5 K in standby mode
  - Cool-down and warm-up

- Cavity helium pressure – 31 mbar
- Cavity helium pressure stability $\pm 0.1$ mbar
- Expected availability during scheduled beam operation – 98%
- Support cool-down or warm-up of the Linac in $< 20$ days
Key Requirements

Cryomodule Static and Dynamic Heat loads

<table>
<thead>
<tr>
<th>CM</th>
<th>No. of CM</th>
<th>2K CW mode, (W)</th>
<th>2K Pulsed mode, (W)</th>
<th>5K Intercept, (W)</th>
<th>70 K Shield, (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HWR</td>
<td>1</td>
<td>61</td>
<td>61</td>
<td>60</td>
<td>250</td>
</tr>
<tr>
<td>SSR1</td>
<td>2</td>
<td>70</td>
<td>26</td>
<td>176</td>
<td>332</td>
</tr>
<tr>
<td>SSR2</td>
<td>7</td>
<td>429</td>
<td>83</td>
<td>434</td>
<td>882</td>
</tr>
<tr>
<td>650 MHz Lowβ</td>
<td>11</td>
<td>633</td>
<td>54</td>
<td>176</td>
<td>528</td>
</tr>
<tr>
<td>650 MHz Highβ</td>
<td>4</td>
<td>535</td>
<td>43</td>
<td>128</td>
<td>344</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>1728</td>
<td>267</td>
<td>974</td>
<td>2336</td>
</tr>
</tbody>
</table>

Requirements are defined and traceable
Cryogenic System Design – Conceptual Design

Used for pulsed mode only
Cryogenic Plant Design – Conceptual Design

- **Baseline**
  - Sub-atmospheric compressor
  - CC3
  - CC2
  - CC1
  - ~51 kPa
  - ~2.7 kPa
  - Distribution Box
  - Cryomodules

- **Alternative**
  - CC5
  - CC4
  - CC3
  - CC2
  - CC1
  - 2.0 K Cold Box
  - 4.5 K Cold Box
  - ~110 kPa
  - ~1.54 kPa
  - Liquid Helium
  - Cryo Distribution

Hybrid cycle design
Cold compression design
PIP-II Cryogenic Distribution System (CDS) – Conceptual Design

- Fully segmented Linac
- Distribution box located in the refrigerator room
- Cryogenic transfer line with bayonet cans that runs parallel to the cryomodules
Auxiliary Systems – Conceptual Design

- Warm and cold interconnect piping
- Warm helium storage tanks
- Liquid helium Dewar
- Helium recovery system
- Initial system purification equipment

Reuse from the Tevatron

Conceptual design is supporting key design requirements
Scope

- PIP-II Cryogenic Plant (121.3.11.2)
- PIP-II Cryogenic Distribution System (121.3.11.3)
- PIP2IT Cryogenic Distribution System (121.3.11.1)
Scope – Cryogenic Plant

• **2kW at 2.0 K Cryogenic plant**
  – Warm recirculation compressors with associated cooling, oil-removal systems and dryers, gas management system, refrigerator cold box(s) with heat exchangers, turbines, cold compressors, plant controls and instrumentation, acceptance test cryostat, and commissioning services ➔ DAE/BARC Deliverables

• **Ancillary support equipment**
  – Warm and cold interconnect piping, helium purification system, helium gas and liquid storage, liquid nitrogen storage – FNAL

• **Plant equipment installation services**
  – Rigging, welding, cabling, leak checking, pressure testing - FNAL
Scope – Cryogenic Distribution System (CDS)

• Design and fabricate components needed to feed and return the cryogens to the Linac components in accordance with functional requirements and other applicable specifications including:
  – Distribution Box
  – Tunnel cryogenic transferlines
  – Cryomodule bayonet can(s)
  – Vacuum insulated jumpers
  – Helium recovery headers
  – Turn around box
  – Pressure safety systems
Scope – PIP2IT Cryogenic Distribution System

- Design, fabricate, install, and commission components needed to feed and return the cryogens to the PIP2IT cryogenic system in accordance with functional requirements and other applicable specifications including:
  - External transferline
  - Cave transferline and turn around box
  - Vacuum insulated jumpers (u-tubes)
  - Cryogenic instrumentation and controls
  - Warm recovery headers
  - Installation and commissioning services
  - Transfer to operation services

Cryogenic system technical scope is defined for FNAL and BARC
Interfaces

Cryogenic System interfaces with the following sub systems:

- Conventional Facilities (WBS 121.5)
- Control System (WBS 121.3.17)
- HWR (WBS 121.3.4)
- HB650 (WBS 121.3.8)
- Installation, Integration, Commissioning (WBS 121.3.22)
- LB650 (WBS 121.3.7)
- Safety Systems (WBS 121.3.20)
- SSR1 (WBS 121.3.5)
- SSR2 (WBS 121.3.6)
- Vacuum System (WBS 121.3.18)

PIP-II DocDB doc#1160-v3  «PIP-II Interface Matrix »

Cryogenic System Interface Control Document (ICD) TC#ED0006893

- Interfaces are defined and documented
- The level of interface details is commensurate for the current project stage
Qualified project personnel are in place at Fermilab and BARC.
Technical Progress to Date - Cryogenic Plant

Hybrid compression cycle

Temperature - Entropy Diagram
## Baseline Cryoplant Specifications

<table>
<thead>
<tr>
<th>Refrigeration</th>
<th>2K (W)</th>
<th>5 – 9K (W)</th>
<th>35 – 75K (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>1,900</td>
<td>1,500</td>
<td>9,100</td>
</tr>
<tr>
<td>Supply Pressure</td>
<td>$2.2 \leq P \leq 4 \text{ bar}$</td>
<td>$2.2 \leq P \leq 4 \text{ bar}$</td>
<td>$3 \leq P \leq 18 \text{ bar}$</td>
</tr>
<tr>
<td>Return Pressure</td>
<td>27 mbar</td>
<td>$2.2 \leq P \leq 4 \text{ bar}$</td>
<td>$3 \leq P \leq 18 \text{ bar}$</td>
</tr>
<tr>
<td>Supply Temp</td>
<td>$\leq 4.5 \text{ K}$</td>
<td>$\leq 4.5 \text{ K}$</td>
<td>$35 – 40 \text{ K}$</td>
</tr>
<tr>
<td>Return Temp</td>
<td>$\leq 3.8 \text{ K}$</td>
<td>$\leq 9 \text{ K}$</td>
<td>$\leq 80 \text{ K}$</td>
</tr>
</tbody>
</table>
Technical Progress to Date - PIP-II Cryogenic Distribution System

- Developed preliminary detailed list of requirements
- Defined preliminary loads, steady-state and transient modes – TC#ED0003531
- Defined preliminary interfaces and boundaries – TC#ED0006893
- Surveyed similar designs
- Refined heat load estimates – TC#ED0003531
- Interface Control Document – TC#ED0006893
- Valve and Instrument List – TC#ED0006894
- CDS Functional Analysis – TC#ED0006895
- Bayonet Box Functional Analysis – TC#ED0006896
- Cryomodule Bayonet Boxes P&ID - TC#ED0006897
- Site Layout of Cryogenic Distribution Lines – TC#ED0006898
- Pressure drop calculations – TC#ED0006899
- Preliminary relief valves calculations – TC#ED0006900
- Preliminary piping layout – TC#ED0006901
Technical Progress to Date - PIP2IT

- External transferline is under fabrication at Fermilab
- Cave transferline design-built contract was awarded to Demaco B.V. Holland
- Integration and installation plans are being developed
Technical Progress to Date - Cave transferline
Technical Progress to Date - CM bayonet boxes
WBS 121.3.11 Design is sufficiently developed and supported for the current state of the project

Alternative solutions have been analyzed
Design Review Plan

- Cryogenic System is subject to Project Reviews
- Divi/Dept review procedures based on the Fermilab Engineering Manual
- Technical reviews (PDR, FDR, PRR whenever appropriate)
- PIP2IT CDS Internal Review – April 2017
  - all recommendations are closed
- PIP2IT Cave TL
  - Preliminary Design Review – October 2017
  - Final Design Review – November 2017
  - Production Readiness Review – January 2018
- Cryogenic Plant
  - ESD review – April 2016
  - BARC committee review – May 2016
    - All recommendations are closed, RFP was issued December 2016
    - PO likely to be released by mid 2018

Appropriate number of engineering and project reviews have been completed or planned
- PIP-II Cryogenic system will use compressed and liquefied Helium

- This presents following potential hazards:
  - Extreme cold hazard
  - Oxygen Deficiency Hazard (ODH)
  - Oxygen enriched hazard
  - Over pressurization or explosion due to rapid expansion
  - High noise levels

- The approach to protection from hazards by minimizing potential hazards at levels as low as is reasonable will be incorporated in a design for the PIP-II Cryogenic system
  - Utilizing National and International Codes and Standards for pressure systems design
  - Segment insulating vacuum (reduces release rate)
  - Move relief valves out of the tunnel wherever possible
  - Pipe all relief valves outside (wherever possible)
  - Reduce heat flux by adding insulation
  - Provide barriers to minimize external effects/damages

- Project ISM and QA plans (docdb #141 and 142)

*Cryogenic System is designed to be safe and to minimize impact on the environment*
BOE Summary

- Labor and M&S estimate cover the entire scope of work defined in the WBS
- Cost Estimating procedure #12.PM-005
- TC#ED0003758 “Assumptions for Cryogenic Components Estimate”
- Historical data and recent vendor quotes are used
- No contingency is included
- P6 contains raw hours and dollars

Cost Estimate is documented using consistent assumptions and is traceable

<table>
<thead>
<tr>
<th>WBS Number</th>
<th>Title</th>
<th>Docdb #</th>
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<tbody>
<tr>
<td>121.3.11.1</td>
<td>PIP2IT CDS</td>
<td>297-v4</td>
</tr>
<tr>
<td>121.3.11.2</td>
<td>PIP-II Cryoplant</td>
<td>300-v3</td>
</tr>
<tr>
<td>121.3.11.3</td>
<td>PIP-II CDS</td>
<td>309-v4</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>121.3.11 - Linac - CRYOgenics (CRYO)</td>
<td>P6 Hours</td>
<td>P6 Base Cost</td>
<td>P6 Base Cost</td>
<td>Total</td>
<td>% of Base</td>
</tr>
<tr>
<td>121.3.11.1 - Linac - CRYO - PIP2IT Cryo Distribution System (CDS)</td>
<td>4,983</td>
<td>$579.2</td>
<td>$696.7</td>
<td>$255.2</td>
<td>20.0%</td>
</tr>
<tr>
<td>121.3.11.2 - Linac - CRYO - PIP-II CryoPlant</td>
<td>27,444</td>
<td>$4,210.6</td>
<td>$5,781.9</td>
<td>$2,935.7</td>
<td>29.4%</td>
</tr>
<tr>
<td>121.3.11.3 - Linac - CRYO - PIP-II Cryo Distribution System (CDS)</td>
<td>25,174</td>
<td>$2,994.6</td>
<td>$4,247.1</td>
<td>$1,873.0</td>
<td>25.9%</td>
</tr>
<tr>
<td>Grand Total</td>
<td>57,601</td>
<td>$7,784.4</td>
<td>$10,725.7</td>
<td>$5,063.9</td>
<td>27.4%</td>
</tr>
</tbody>
</table>

Note: P6 base cost = BOE + overheads and escalation

- Oversee delivery of all scope of WBS 121.11.3
- Costs generated from resource loaded schedule
- Estimate developed by people experienced with cryogenics. Estimate Uncertainty follows project guidelines
- Collaborative methods used while developing cost estimate assumptions
- Assumptions are realistic and used consistently
Cost Drivers and Estimate Maturity

- Design, fabricate, procure, and install PIP2IT CDS components
- Cryogenic plant contract oversight, cryogenic plant and associated auxiliary systems installation and commissioning
- Design, fabricate, procure, and install PIP-II CDS components
- Cost drivers identified
We understand our funding demands
Labor profile is consistent with WBS121.11.3 scope needs and can be supported.
Two high risks associated with Cryogenic System are documented in the Risk Register

1. Pulsed and CW cryomodule operating modes cause cryogenic or mechanical instabilities
2. Insufficient Cryogenic system vendor manufacturing capacity and priority

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsed and CW cryomodule operating modes cause cryogenic or mechanical instabilities</td>
<td>50.00%</td>
<td>4 (H)</td>
<td>688</td>
<td>3.3</td>
<td>2 (M)</td>
<td>3 (H)</td>
<td>3 (High)</td>
</tr>
<tr>
<td>Insufficient Cryogenic system vendor manufacturing capacity and priority</td>
<td>50.00%</td>
<td>4 (H)</td>
<td>500</td>
<td>3.5</td>
<td>2 (M)</td>
<td>3 (H)</td>
<td>3 (High)</td>
</tr>
</tbody>
</table>

Risks associated with delay of the Cryogenic Plant delivery is included in the PIP-II Project Risk section of the Risk Register – see presentation by S. Mishra
Schedule

Charge #2
Summary

- Cryogenic system technical scope is defined
- Functional performance requirements and key interfaces are identified
- Strategy and technical solutions to support wide range of cryogenic load is developed
- WBS 121.3.11 design is sufficiently developed and is supported for the current state of the project
- CDS and Cryoplant are being designed as a single system with safety considerations in the design phase
- Cost and schedule are understood
- Detailed budget and schedule, in P6, are structured to achieve the technical scope
- Qualified project team is in place both at FNAL and BARC

We are ready for CD-1
Thank you!