SRF and Cryogenics (121.02)

Genfa Wu

PIP-II Independent Project Review

4-6 December 2018

In partnership with:
India/DAE
Italy/INFN
UK/STFC
France/CEA/Irfu, CNRS/IN2P3
Outline

- Scope/Deliverables
- Requirements
- Interfaces
- Preliminary Design, Maturity
- Design Review Plan
- Technical Progress to Date
- Organization
- Steps to CD-2
- ESH&Q
- Risks and Mitigations
- Responses to CD-1 recommendations
- Breakout Session topics
- Summary
About Me:

• System Manager for SRF and Cryogenics (L2)
• Previously
  – Deputy Department Head of SRF Measurement and Research
  – Deputy CAM of LCLS-II Cryomodule at Fermilab
  – Cryomodule Group Leader at FRIB
  – SPX Cryomodule L4 CAM of APS Upgrade
# 121.02 SRFCRYO System Requirements

<table>
<thead>
<tr>
<th>#</th>
<th>Scope</th>
<th>Threshold KPP</th>
<th>Objective KPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SRF Linac Beam Energy</td>
<td>600 MeV</td>
<td>800 MeV</td>
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<tr>
<td>2</td>
<td>Linac Beam</td>
<td>Beam delivered to the Beamline Dump</td>
<td>5.4E12 particles per pulse (H-) at 20 Hz beam delivered to the Beamline Dump</td>
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<tr>
<td>3</td>
<td>Booster/Recycler/Main Injector upgrades</td>
<td>Booster injection region, Recycler RF upgrades, and Main Injector RF upgrades, hardware installed and tested without beam in respective machines.</td>
<td>Linac beam injected and circulated in the Booster</td>
</tr>
<tr>
<td>4</td>
<td>Cryogenic Infrastructure</td>
<td>Cryogenic plant and associated distribution system are installed and capable to support cavities operation at 2 K</td>
<td>Cryogenic system installed and is capable to support Linac operation in CW mode</td>
</tr>
</tbody>
</table>

**PIP-II Systems Function and Configuration Document:**

SRF and CRYO System, ED0008595
### Scope and Deliverables

#### SRF

<table>
<thead>
<tr>
<th>Cryomodule</th>
<th>Number (Prototype + installed)</th>
<th>Cavity Number</th>
<th>Magnet Number</th>
<th>Testing</th>
<th>Note</th>
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<tbody>
<tr>
<td>HWR</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>Tested at FNAL</td>
<td>ANL Led Design</td>
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<tr>
<td>SSR1</td>
<td>1+2</td>
<td>8</td>
<td>4</td>
<td>Tested at FNAL</td>
<td>FNAL Led Design</td>
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<tr>
<td>SSR2</td>
<td>1+7</td>
<td>5</td>
<td>3</td>
<td>Tested at FNAL</td>
<td>Integrated Design</td>
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<tr>
<td>LB650</td>
<td>1+11</td>
<td>3</td>
<td>0</td>
<td>Partial Test at Partner lab, Full Test at FNAL</td>
<td>Integrated Design</td>
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<tr>
<td>HB650</td>
<td>1+4</td>
<td>6</td>
<td>0</td>
<td>Test at FNAL</td>
<td>Integrated Design</td>
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<tr>
<td><strong>Total</strong></td>
<td>4+25</td>
<td>116</td>
<td>37</td>
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</table>

**CRYO**

- Cryoplant 2.2 kW 2K capacity
- Cryogenic distribution to support 2K CW operation and appropriate cool down of Linac

*Four prototype cryomodules were added to reduce project risk*
## In-kind Contribution

<table>
<thead>
<tr>
<th>Item</th>
<th>US DOE</th>
<th>In-kind</th>
<th>Note</th>
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<tbody>
<tr>
<td>HWR Cryomodule</td>
<td>ANL builds cryomodule, FNAL tests.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSR1 Cryomodules</td>
<td>FNAL builds all Cryomodules</td>
<td>Some prototype cavities, All production cavities, tuners and solenoids</td>
<td></td>
</tr>
<tr>
<td>SSR2 Cryomodules</td>
<td>FNAL builds Prototype and Production CMs</td>
<td>Some prototype cavities, All production cavities, tuners and solenoids</td>
<td></td>
</tr>
<tr>
<td>LB650 Cryomodules</td>
<td>FNAL tests all cryomodules</td>
<td>Prototype and production cryomodules including all sub components</td>
<td>Cavities from different partner lab</td>
</tr>
<tr>
<td>HB650 Cryomodules</td>
<td>• FNAL builds and tests prototype cryomodule and transportation tests</td>
<td>• Production cryomodules including all subcomponents</td>
<td>Couplers from different partner lab</td>
</tr>
<tr>
<td></td>
<td>• FNAL builds one production cryomodule.</td>
<td>• Transportation design and procurement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• FNAL tests all production CMs</td>
<td></td>
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</tr>
<tr>
<td>Cryoplant</td>
<td>FNAL installation and commissioning</td>
<td>Cryoplant Procurement</td>
<td></td>
</tr>
<tr>
<td>Cryogenic Distribution</td>
<td>FNAL design, procurement, installation and commissioning</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Cryomodule Repair after Delivery is Fermilab Responsibility**
Cryomodule Schedule

27 November 2018 – Critical path on SSR2

Fiscal year

**Legend**
- ◆ Start Cavities Cold Tests
- ▲ Start String Assembly
- ⬤ Start CM RF Testing

**Fiscal year**

<table>
<thead>
<tr>
<th>Charge #5</th>
<th>SSR1</th>
<th>SSR2</th>
<th>LB650</th>
<th>HB650</th>
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<tbody>
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<td>FY2027</td>
<td>F</td>
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# 121.02 L3 Functional Requirement Specifications

<table>
<thead>
<tr>
<th>WBS #</th>
<th>L3 System</th>
<th>TeamCenter ED#</th>
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<tbody>
<tr>
<td>121.02.02</td>
<td>Half Wave Resonator Cryomodule</td>
<td>ED0001313</td>
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<tr>
<td>121.02.03</td>
<td>Spoke Resonator One Cryomodule</td>
<td>ED0001316</td>
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<tr>
<td>121.02.03</td>
<td>Spoke Resonator Two Cryomodule</td>
<td>ED0001829</td>
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<tr>
<td>121.02.04</td>
<td>Low Beta 650 MHz Cryomodule</td>
<td>ED0001830</td>
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<tr>
<td>121.02.04</td>
<td>High Beta 650 MHz Cryomodule</td>
<td>ED0001322</td>
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<tr>
<td>121.02.05</td>
<td>Cryogenic Plant</td>
<td>ED0003531</td>
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<tr>
<td>121.02.06</td>
<td>Cryogenic Distribution</td>
<td>ED0008022</td>
</tr>
</tbody>
</table>

*FRS are being reviewed by all partner labs*
Interfaces

• Internal
  – Cryomodules and Cryogenic Distribution System
  – Cryomodules and Cryogenic Plant
  – Cryogenic Plant and Cryogenic Distribution System

• External
  – SRFCRYO and Accelerator
  – SRFCRYO and Linac Installation and Beam Commissioning
  – SRFCRYO and Conventional Facility

• Partner Labs
  – Governed by Project Planning Document
  – ICD are agreed by all partner labs

All Interface Documents are drafted and currently under review by all partner labs
Prototyping before production to allow feedback to designs
Preliminary Design and Design Maturity

- **HWR**
  - Final design review completed.
  - Assembly preparation is in progress

- **SSR1**
  - String assembly and cold mass assembly final design review completed.
  - String assembly is in progress

- **SSR2**
  - Cavity Design is in progress. Jacketed cavity preliminary design review is schedule in March 2019, and final design review is scheduled in October 2019
  - FRS and ICD are being reviewed.

- **LB650**
  - Cavity Design and Prototype is in progress at partner labs.
  - FRS and ICD are being reviewed

- **HB650**
  - Jacketed cavity preliminary design is scheduled in the week of 11/26/2018
  - Horizontal test validation of critical components is scheduled in February 2019
  - Cryomodule conceptual 3D model is completed with preliminary transportation analysis

- **Cryogenic Plant**
  - Vendor Proposals were received, technical evaluation is complete and commercial evaluation is in progress. Signed contract is expected at the end of CY18. Integration Preliminary design scheduled for July 2019

- **Cryogenic Distribution System**
  - Preliminary Design is in progress

*Expected 64% design maturity by June 2019*
## Design Review Plan – Past Reviews

<table>
<thead>
<tr>
<th>Type of Review</th>
<th>Component</th>
<th>Date</th>
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<tbody>
<tr>
<td>Preliminary Design Review</td>
<td>SSR1 RF Coupler</td>
<td>20-Feb-12</td>
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<tr>
<td>Final Design Review</td>
<td>HWR Cavity</td>
<td>17-May-12</td>
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<tr>
<td>Preliminary Design Review</td>
<td>HWR Cryomodule</td>
<td>16-May-13</td>
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<td>Final Design Review</td>
<td>HWR Cryomodule</td>
<td>15-Oct-13</td>
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<tr>
<td>Preliminary Design Review</td>
<td>SSR1 Integrated CM</td>
<td>03-Nov-15</td>
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<tr>
<td>Final Design Review</td>
<td>HB650 B.90 Bare Cavity</td>
<td>21-Dec-15</td>
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<tr>
<td>Preliminary Design Review</td>
<td>LB650 Bare Cavity</td>
<td>15-Jul-16</td>
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<tr>
<td>Preliminary Design Review</td>
<td>SSR1 Tuner</td>
<td>09-Sep-16</td>
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<tr>
<td>Final Design Review</td>
<td>SSR1 pCM Jacketed Cavity</td>
<td>28-Sep-16</td>
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<tr>
<td>Production Readiness Review</td>
<td>SSR1 Prototype Tuner</td>
<td>01-Nov-16</td>
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<tr>
<td>Preliminary Design Review</td>
<td>SSR1 Prototype CM String</td>
<td>02-Feb-17</td>
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<tr>
<td>Final Design Review</td>
<td>HB650 Prototype RF Coupler</td>
<td>10-Feb-17</td>
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<tr>
<td>Final Design Review</td>
<td>Spoke Test Cryostat Upgrade</td>
<td>08-Mar-17</td>
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<tr>
<td>Preliminary Design Review</td>
<td>650 MHz Prototype Tuner</td>
<td>29-Jun-17</td>
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<td>LB650 Jacketed Cavity</td>
<td>20-Jul-17</td>
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<td>Status Review</td>
<td>SSR2 Prototype bare cavity</td>
<td>07-Nov-17</td>
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<td>Final Design Review</td>
<td>SSR1 Prototype CM String</td>
<td>12-Jan-18</td>
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<td>FDR/PRR</td>
<td>SSR1 Prototype CM Coldmass</td>
<td>11-Jul-18</td>
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<tr>
<td>Conceptual Design Review</td>
<td>HWR Transportation</td>
<td>14-Aug-18</td>
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<tr>
<td>Production Readiness Review</td>
<td>HWR Resources &amp; Schedule</td>
<td>30-Aug-18</td>
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Extensive reviews were planned to ensure all critical components are successful.
## Design Review Plan – Outlook

<table>
<thead>
<tr>
<th>Preliminary Design Review</th>
<th>Description</th>
<th>Date</th>
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<tbody>
<tr>
<td>Preliminary Design Review</td>
<td>HB650 Jacketed Cavity B.90</td>
<td>30-Nov-18</td>
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<tr>
<td>Preliminary Design Review</td>
<td>HB650 Tuner</td>
<td>15-Dec-18</td>
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<tr>
<td>Preliminary Design Review</td>
<td>LB650 Jacketed Cavity (FNAL, INFN, DAE)</td>
<td>02-Jan-19</td>
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<td>Preliminary Design Review</td>
<td>CDS</td>
<td>22-Jan-19</td>
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<tr>
<td>Preliminary Design Review</td>
<td>SSR2 Jacketed Cavity (FNAL and Intl Partners)</td>
<td>15-Mar-19</td>
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<td>Preliminary Design Review</td>
<td>SSR1 Transportation Tooling</td>
<td>27-Mar-19</td>
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<td>Preliminary Design Review</td>
<td>HB650 String Assembly</td>
<td>01-Apr-19</td>
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<tr>
<td>Preliminary Design Review</td>
<td>HB650 Cold Mass Assembly</td>
<td>01-Apr-19</td>
</tr>
<tr>
<td>Preliminary Design Review</td>
<td>HB650 Cryomodule Integration</td>
<td>01-Apr-19</td>
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</tbody>
</table>
Progress to date – HWR Status

- All major components design validated, procured, received and accepted.
  - Cavity, Tuner, Coupler, Solenoid, cold mass support and Vacuum vessel.
- Mockup Assembly and Cool down completed.
- Cavity/coupler integrated acceptance tests are in progress.
  - All 8 cavity/coupler assembly were qualified in horizontal tests.
- Transportation Design is in progress
- String assembly, cold mass assembly and cryomodule assembly will start in December 2018
- Cryomodule completion in April 2019.
Progress to date – SSR1 Status

- Major components design validated, procured, received and accepted.
  - Cavity, Tuner, Coupler, Solenoid and Vacuum vessel.
- Cavity/coupler integrated acceptance tests are in progress.
  - All 8+1 cavity/coupler/tuner assemblies were qualified in horizontal integrated tests. One is contributed by IIFC, India
- Mock-up assembly completed.
- Final Design Review and Production Readiness Review are scheduled.
- String assembly started.
- Cryomodule assembly completes in May 2019.
SSR2 Overview

- RF design completed
- Cavity mechanical design is in progress
- SSR1 Coupler power capability demonstrated at >20 kW.
LB650 Overview

• Cavity RF Design Completed.
• Prototype Bare Cavities are Being Procured.
  – Two prototype bare cavities are to be delivered in July 2019
• Dressed Cavity Mechanical Design is in Progress.
  – IIFC optimized the mechanical design for CW operation
HB650 Overview

- Cavity RF design completed.
- Cavity mechanical design completed.
- Cavity high Q R&D is in progress.
- Jacketed cavity design validation is in progress.
- Coupler design validation is in progress.
- Conceptual transportation analysis completed.
- A preliminary design choice was made to adopt strong back design.
- Cryomodule design is in progress.

New coupler design passed particle free test
First HB650 tuner meets spec
Charge #1, 2
First HB650 cavity is to be dressed.
HB650 Cryomodule Design Features

• Support High Q
  – Cryogenic Supports Fast Cool Down
  – Cryomodule Thermal Design to Minimize Thermoelectric Current
  – Magnetic Shield to Minimize Ambient Earth Magnetic Field
  – Better Instrumentation for High Q operation

• Designed to be compatible for transportation
**Progress to Date – Cryogenic Plant**

Cryoplant bids received and evaluation is in progress

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<tr>
<td></td>
<td>W</td>
<td>g/s</td>
<td>g/s</td>
<td>bara</td>
<td>bara</td>
<td>K</td>
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<tr>
<td>2K</td>
<td>2163*</td>
<td>138</td>
<td>110</td>
<td>2.2 &lt; P &lt; 4</td>
<td>P - 0.03</td>
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<td>4.5K</td>
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<td>HTTS</td>
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<td>3 &lt; P &lt; 18</td>
<td>P - 0.28</td>
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</tbody>
</table>
Progress to Date – Cryogenic Distribution System

CDS 40% design complete, cold box design choice pending
Next Steps toward CD-2/3a

- Complete HWR Cryomodule Assembly in April 2019
- Complete SSR1 Prototype Cryomodule Assembly in May 2019
- Complete SSR2 Jacketed Cavity Preliminary Design Review in March 2019
- Complete HB650 ($\beta=0.90$) Horizontal Cavity Test in May 2019
- Complete LB650 Jacketed Cavity Preliminary Design Review in April 2019
- Award Cryoplant Contract in December 2018 and progress towards preliminary design review of building integration in July 2019
- Complete Preliminary Design Review for Cryogenic distribution system in January 2019
ESH

- Fermilab
  - Design follows Fermilab Engineering Manual
  - Cavity processing follows FESHM for chemical hygiene practice
  - Cavity and cryomodule testing follows FESHM for ODH guidelines and radiation safety
  - Pressure Safety:
    - Cavities follow Fermilab FESHM Pressure Safety
    - HWR and SSR Cryomodules follow ASME pressure safety guidelines
    - 650 Cryomodules follows PED (Europe) standard.

- Partner Labs
  - Indian partner labs follow ASME standard
  - European partner labs follow PED standard

PED are equivaled to ASME
Quality Management

- Quality Planning at Fermilab
  - Critical Quality Elements
  - QC Plans
    - Travelers
    - Incoming Inspections
    - Acceptance Testing
    - Training
    - Work Controls
    - Procurement Quality / Supplier Quality
    - Issues Management (Corrective Action/Preventive Actions)
  - Traceability of quality control to requirements
  - Lessons Learned (in process)
Quality Management

• QA Expectations for Partners and Vendors
  – Critical Quality Elements
    • Acceptance Criteria for all parts
    • Acceptance Test Plans
  – Partner Quality Assurance Plans or Vendor QA Plans
    • QC Plans
    • Manufacturing Inspection/Test Plans
    • Hold points / witness points
    • Verification of requirements
    • Issues Management (CA/PA)
  – Routine site visits
  – Imbedded work force in some partner labs
**SRF and Cryogenics Risks**

- High Risks: 7
- Medium Risks: 15
- Low Risks: 5

### High Risks

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<tr>
<th>RI-ID</th>
<th>Title</th>
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<td>RT-121-02-001</td>
<td>650 Cryomodule is damaged during transportation</td>
</tr>
<tr>
<td>RT-121-02-003</td>
<td>Underestimated resources for design optimization of SSR1 CM (1)</td>
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<tr>
<td>RT-121-02-003-B</td>
<td>Underestimated resources for design optimization of HB650 CM (1)</td>
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<tr>
<td>RT-121-02-003-C</td>
<td>Underestimated resources for design optimization of SSR2 CM (1)</td>
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<tr>
<td>RT-121-02-004</td>
<td>SRF pre-production input couplers are unreliable</td>
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<tr>
<td>RT-121-02-005</td>
<td>650 MHz IOT Amplifiers fail</td>
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<tr>
<td>RT-121-02-006</td>
<td>Cryomodule production rate at Fermilab is too slow</td>
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</tbody>
</table>

*Most high risks will be retired by CD-3 except -001, -006*
Conducted transportation analysis of two leading CM design concepts: strong-back (SSR1) and spaceframe (ESS, SNS)

Held 650 MHz cryomodule design advisory meeting
- Hasan Padamsee, Robert Laxdal, Michael Kelly, Thomas Peterson, Ed Daly, Mark Wiseman, Joel Fuerst

Preliminary analysis showed no technical preference in terms of shipping and alignment

Final decision considered: Technical evaluation; Schedule & Cost impact; CEA & other partners considerations;

A preliminary design choice was made in November to adopt strong back design

RLS includes shipping proto HB650 from US to Europe and back
Transportation Risk of 650 MHz Cryomodule

- Transportation is Part of the Cryomodule Prototyping
- Transportation Studies (three trips)
  - HB650 Prototype Cryomodule
    - Fully Tested
    - FNAL to Europe
    - Test Optional
    - Europe to FNAL
    - Verification Test
  - LB650 Prototype Cryomodule
    - Partially Tested
    - Europe to FNAL
    - Verification Test
### Response to Recommendations – Summary

<table>
<thead>
<tr>
<th>ID</th>
<th>Risk Description</th>
<th>Status</th>
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<tbody>
<tr>
<td>98027</td>
<td>Define operational gradient margin and cryomodule maintenance strategy to meet the performance specification of 90% reliability with only 8 weeks of maintenance per year by CD-2.</td>
<td>In Progress. Expected to complete before CD2</td>
</tr>
<tr>
<td>98029</td>
<td>Convene an external review to address expediting the SSR2 prototype and advancing an LB650 prototyping effort by CD-2.</td>
<td>Addressed</td>
</tr>
<tr>
<td>98530</td>
<td>Use first prototypes to study long-distance transport of accelerator modules</td>
<td>Addressed</td>
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<tr>
<td>98536</td>
<td>Validate 'particle-free' assembly for 650-MHz couplers</td>
<td>Addressed</td>
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</table>
## Response to Recommendations (1)

### Charge # 8

**System**
- SRF and CRYO

**Owner**
- G. Wu

### Recommendation

Define operational gradient margin and cryomodule maintenance strategy to meet the performance specification of 90% reliability with only 8 weeks of maintenance per year by CD-2.

### Project Response

- Operational gradient margin will be established in TRS documents of all the cryomodules. TRS documents are being drafted.
- Cryomodule maintenance strategy is being drafted.

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**PIP-II CD1 Review Recommendation No.13**

- **Status:** Open
- **Planned Date Closed:** 01/31/2019
Response to Recommendations (2)

**Charge # 8**

### PIP-II CD1 Review Recommendation No.15

<table>
<thead>
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<th>System</th>
<th>SRF and CRYO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Owner</strong></td>
<td>G. Wu</td>
</tr>
<tr>
<td><strong>Recommendation</strong></td>
<td>Convene an external review to address expediting the SSR2 prototype and advancing an LB650 prototyping effort by CD-2.</td>
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<tr>
<td><strong>Project Response</strong></td>
<td>SSR2 and LB650 have been advanced in current scope. No external review is needed. Overall schedule will meet CD4 milestone with prototyping effort completed in 2022 (SSR2) and 2023 (LB650)</td>
</tr>
</tbody>
</table>

**Status:** Open

**Planned Date Closed:** 04/08/2019
Response to Recommendations (3)

**PIP-II P2MAC Review Recommendation No.R2**

<table>
<thead>
<tr>
<th>System</th>
<th>SRF and CRYO</th>
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</thead>
<tbody>
<tr>
<td>Owner</td>
<td>G. Wu</td>
</tr>
<tr>
<td>Recommendation</td>
<td>Use first prototypes to study long-distance transport of accelerator modules</td>
</tr>
<tr>
<td>Project Response</td>
<td>HB650 prototype cryomodule transportation studies are in current scope in 2021. LB650 Prototype cryomodule shipping test is in 2024</td>
</tr>
</tbody>
</table>

Status: Open
Planned Date Closed: 06/01/2022
### PIP-II P2MAC Review Recommendation No.R8

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Owner</td>
<td>G. Wu</td>
</tr>
<tr>
<td>Recommendation</td>
<td>Validate 'particle-free' assembly for 650-MHz couplers</td>
</tr>
</tbody>
</table>
| Project Response | • Coupler assembly of copper shield design has been validated in clean room.  
• Coupler assembly of copper plating design is in progress. |

**Status:** Open  
**Planned Date Closed:** 12/31/2018
Breakout Sessions

• SC3 Breakout Session
  – G. Wu: SRF and Cryogenics Overview
  – Z. Conway: HWR Cryomodule Overview
  – D. Passarelli: SSR Cryomodule Overview
  – S. Chandrasekaran: 650 MHz Cryomodule Overview
  – A. Dalesandro: Cryogenic Distribution System

• SC3/5 Joint Breakout Session
  – B. Hansen: CryoPlant Requirements and Design
Summary

- System Functions and Configuration is drafted
- FRS and ICD are drafted and currently being reviewed
- HWR and SSR1 prototype cryomodule assembly are in progress
- HB650, LB650 and SSR2 designs are in progress
- Cryoplant contract award soon
- Cryoplant building and Cryogenic distribution designs are in progress
- ESH and QA plans are developed
- In-kind contribution, sufficient prototyping to retire risks
- SRF and Cryogenic technical team is motivated, experienced and ready to deliver

We are on track for CD-2/3a and look forward to your feedback
Thank you for your attention