121.02.03 SRF - Single Spoke Resonator Cryomodules

SRF and Cryogenics Breakout Session

Donato Passarelli
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 from partners
• Requirements
• Interfaces
• Preliminary Design, Maturity
• Technical Progress to Date
• ESH&Q
• Risks and Mitigations
• Summary
About Me:

• Donato Passarelli
  – L3 Manager for SSR cavities and cryomodules
  – Group Leader, Mechanical Engineering in APS-TD
  – Working in the SRF field (SSR at FNAL) since 2010
  – PhD in Mechanical Engineering on SSR1 cavities and tuner
Design, procurement, fabrications and testing of the Single Spoke Resonator (SSR1, SSR2) cavities and cryomodules

Final scope will be delivery of tested CMs for installation into PIP-II tunnel

<table>
<thead>
<tr>
<th></th>
<th>SSR1</th>
<th>SSR2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong># CMs</strong></td>
<td>1+2</td>
<td>1+7</td>
</tr>
<tr>
<td><strong>Cavities per CM</strong></td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td><strong>Solenoids per CM</strong></td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td><strong>CM configuration</strong></td>
<td>4x (csc)</td>
<td>sccscscsc</td>
</tr>
<tr>
<td><strong>CM length (m)</strong></td>
<td>5.2</td>
<td>6.5</td>
</tr>
</tbody>
</table>
121.02.03 SSR Scope and Deliverables

SSR1, SSR2 International Partners:

India

France
### 121.02.03 SSR Scope and Deliverables

#### SSR1 proto CM
- **Cryomodule**: 1
- **Jacketed Cavities**: 8
- **Couplers**: 8
- **Tuners**: 8
- **SC Solenoids**: 4
- **Cold BPMs**: 4

#### SSR1 CM1-2
- **Cryomodule**: 2
- **Jacketed Cavities**: 16
- **Couplers**: 16
- **Tuners**: 16
- **SC Solenoids**: 8
- **Cold BPMs**: 8

#### SSR2 proto CM
- **Cryomodule**: 1
- **Jacketed Cavities**: 5
- **Couplers**: 5
- **Tuners**: 5
- **SC Solenoids**: 3
- **Cold BPMs**: 3

#### SSR2 CM1-7
- **Cryomodule**: 7
- **Jacketed Cavities**: 35
- **Couplers**: 35
- **Tuners**: 35
- **SC Solenoids**: 21
- **Cold BPMs**: 21

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**CM assembly and final qualification testing at Fermilab**
121.02.03.02 SSR1 Scope and Deliverables

• **SSR1 Prototype CM**
  – FNAL scope:
    • Qualification of 8 jacketed cavities with coupler and tuner
    • Complete procurement, QA/QC and integration of all cryomodule components
    • RF testing and verification of cryomodule performance at PIP2IT
  – Partners deliverables:
    • 2 jacketed cavities, 2 tuners
  – FNAL deliverables:
    • delivery of tested and qualified proto SSR1 CM at PIP2IT

• **SSR1 Production CMs (1, 2)**
  – FNAL scope:
    • Finalization of design and procedures using lessons learned from proto CM
    • Testing and qualification of 16 fully integrated cavities
    • Procurement, QA/QC, assembly and integration of the full cryomodules
    • RF testing and verification of cryomodule performance at PIP2IT
  – Partners deliverables:
    • 18 Jacketed cavities, 16 tuners, 10 SC solenoids
  – FNAL deliverables:
    • delivery of 2 tested and qualified CMs for installation at PIP-II tunnel
121.02.03.02 SSR2 Scope and Deliverables

• SSR2 Prototype CM
  – FNAL scope:
    • Design/support partners to design cavities and cryomodule components
    • Fabrication of prototype cavities, tuners, couplers
    • Testing and qualification of fully integrated cavities
    • Procurement, QA/QC, assembly and integration of all cryomodule components
    • RF testing and verification of cryomodule performance at PIP2IT
  – Partners deliverables:
    • 6 jacketed cavities, 6 tuners, 7 couplers, 4 SC solenoids
  – FNAL deliverables:
    • tested and qualified proto SSR1 CM at PIP2IT

• SSR2 Production CMs (1…7)
  – FNAL scope:
    • Finalization of design and procedures using lessons learned from proto CM
    • Testing and qualification of fully integrated cavities
    • Procurement (1…6), QA/QC, assembly and integration of the full cryomodules
    • RF testing and verification of cryomodule performance at PIP2IT
  – Partners deliverables:
    • 45 jacketed cavities, 45 couplers, 42 tuners, 23 SC solenoids, all CM components for the 7th CM
  – FNAL deliverables:
    • 7 tested and qualified CMs for installation at PIP-II tunnel
121.02.03 System Requirements

Functional Requirement Specification (FRS) are defined and traceable in Teamcenter:

- SSR1 cryomodule: TC# ED0001316
- SSR2 cryomodule: TC# ED0001829

<table>
<thead>
<tr>
<th>Main Cryomodule Parameters</th>
<th>Units</th>
<th>SSR1</th>
<th>SSR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy for section</td>
<td>MeV</td>
<td>10.3 to 35</td>
<td>35 to 185</td>
</tr>
<tr>
<td>Cavities (solenoids) per cryomodule</td>
<td></td>
<td>8 (4)</td>
<td>5 (3)</td>
</tr>
<tr>
<td>Cryomodule flange-to-flange length</td>
<td>m</td>
<td>≤ 5.4</td>
<td>≤ 6.5</td>
</tr>
<tr>
<td>2 K heat load</td>
<td>W</td>
<td>&lt; 50</td>
<td>&lt; 75</td>
</tr>
<tr>
<td>5 K heat load</td>
<td>W</td>
<td>&lt; 80</td>
<td>&lt; 80</td>
</tr>
<tr>
<td>30 – 50 K heat load</td>
<td>W</td>
<td>&lt; 255</td>
<td>&lt; 250</td>
</tr>
<tr>
<td>Environmental magnetic field</td>
<td>mG</td>
<td>≤ 15</td>
<td>≤ 15</td>
</tr>
<tr>
<td>Transverse cavity (solenoids) alignment error, RMS</td>
<td>mm</td>
<td>≤ 1 (0.5)</td>
<td>≤ 0.5 (0.5)</td>
</tr>
<tr>
<td>Angular cavity (solenoids) alignment error, RMS</td>
<td>mrad</td>
<td>≤ 5 (0.5)</td>
<td>≤ 5 (0.5)</td>
</tr>
</tbody>
</table>

*Table of main cryomodules requirements*
### 121.02.03 System Requirements

- SSR1 cavities
- SSR2 cavities

<table>
<thead>
<tr>
<th>Main Cavities Parameters</th>
<th>Units</th>
<th>SSR1</th>
<th>SSR2</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>MHz</td>
<td>325</td>
<td>325</td>
</tr>
<tr>
<td>$\beta_g (\beta_{opt})$</td>
<td></td>
<td>0.186 (0.222)</td>
<td>0.398 (0.475)</td>
</tr>
<tr>
<td>Aperture diameter (Effective length)</td>
<td>mm</td>
<td>30 (205)</td>
<td>40 (438)</td>
</tr>
<tr>
<td>Operating energy gain per cavity</td>
<td>MV</td>
<td>2.05</td>
<td>5</td>
</tr>
<tr>
<td>Unloaded cavity quality factor ($Q_0$) at 2K</td>
<td></td>
<td>$0.6 \times 10^{10}$</td>
<td>$0.8 \times 10^{10}$</td>
</tr>
<tr>
<td>Cavity operating temperature</td>
<td>K</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>MAWP at room temperature (at 2K)</td>
<td>bar</td>
<td>&gt; 2.05 (4.1)</td>
<td>&gt; 2.05 (4.1)</td>
</tr>
<tr>
<td>Sensitivity to LHe pressure fluctuations</td>
<td>Hz/mbar</td>
<td>&lt; 25</td>
<td>&lt; 25</td>
</tr>
<tr>
<td>Lorentz Force Detuning coefficient</td>
<td>Hz/(MV/m)$^2$</td>
<td>&lt; 5</td>
<td>&lt; 2.8</td>
</tr>
<tr>
<td>Coupler testing power (in full reflection)</td>
<td>kW</td>
<td>10</td>
<td>20</td>
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### 121.02.03 Interfaces

<table>
<thead>
<tr>
<th>L2 Sys</th>
<th>L3 WBS</th>
<th>L3 System Name</th>
<th>L3 Sys</th>
<th>ICD TC ID</th>
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<tbody>
<tr>
<td>SRFCryo</td>
<td>121.2.03</td>
<td>Single Spoke Resonator Cryomodule (SSR)</td>
<td>SSR</td>
<td>ED0007565</td>
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</table>

**Diagram:**

- **121.03.03 High Power RF**
- **121.03.04 Low Level RF**
- **121.03.05 Magnet PS**
- **121.03.06 Vacuum**
- **121.03.02 Accelerator Physics**
- **121.02.06 Cryo Distribution Systems**
- **121.02.05 Cryo Plant**
- **121.06.05 Linac Complex**
- **121.04.03 Test Infrastructure**
- **121.03.07 Controls**
- **121.03.09 Beam Instr.**

**Summary:**

Interfaces are identified and revision controlled documents exist in Teamcenter.
SSR1 cavities

- 8 fully integrated cavities were tested and qualified
  - S104, S106, S109, S110, S111, S112, S113, S114
  - S107 is conditionally qualified and it will serve as spare one
SSR1 cavities performance

<table>
<thead>
<tr>
<th>Cavity ID #</th>
<th>Type</th>
<th>Date of test, yyyy-mm-dd</th>
<th>Q0, x10e8 @10 MV/m</th>
<th>Eacc max, MV/m</th>
<th>Rad. onset field, MV/m</th>
<th>Rad, mR/h @10 MV/m</th>
<th>Rad, mR/h @Eacc max</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1F-IU-104</td>
<td>A</td>
<td>2018-10-07</td>
<td>110</td>
<td>14.4</td>
<td>13</td>
<td>0</td>
<td>45</td>
</tr>
<tr>
<td>S1H-NR-106</td>
<td>B</td>
<td>2018-08-19</td>
<td>80</td>
<td>14.4</td>
<td>12.7</td>
<td>0</td>
<td>153</td>
</tr>
<tr>
<td>S1H-NR-109</td>
<td>A</td>
<td>2018-10-21</td>
<td>64</td>
<td>11.7</td>
<td>9.3</td>
<td>27</td>
<td>170</td>
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<tr>
<td>S1H-NR-110</td>
<td>A</td>
<td>2018-09-29</td>
<td>133</td>
<td>14.4</td>
<td>11</td>
<td>0</td>
<td>666</td>
</tr>
<tr>
<td>S1H-NR-111</td>
<td>A</td>
<td>2018-06-13</td>
<td>90</td>
<td>14.4</td>
<td>n/a</td>
<td>0</td>
<td>0</td>
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<tr>
<td>S1H-NR-112</td>
<td>B</td>
<td>2018-04-10</td>
<td>83</td>
<td>14.4</td>
<td>n/a</td>
<td>0</td>
<td>0</td>
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<tr>
<td>S1H-NR-113</td>
<td>B</td>
<td>2018-05-17</td>
<td>122</td>
<td>14.4</td>
<td>n/a</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>S1H-NR-114</td>
<td>B</td>
<td>2018-09-09</td>
<td>121</td>
<td>14.4</td>
<td>14.4</td>
<td>0</td>
<td>9</td>
</tr>
</tbody>
</table>

\( \frac{df}{dp} \) for all cavities with tuner engaged:
- \( 4 \leq \frac{df}{dp} \leq 10 \text{ Hz/Torr} \)

LFD coefficient for all cavities with tuner engaged:
- \( 4 \leq \text{LFD coeff.} \leq 7 \text{ Hz/(MV·m)}^2 \)

All 8 cavities were found within the frequency target range at 2k
SSR1 cavities S103 and S104 from partners

- Components for He Jacketing for two cavities S103 and S104 were manufactured in house at BARC, Mumbai
- He Jacketing followed by RF measurement and Pressure testing were done on the Dressed cavity prior to shipping to FNAL
SSR1 couplers

• 8 vacuum end couplers were successfully:
  – QC inspected
  – qualified at room temperature on the RF test stand (10 kW full reflection)
  – cleaned and particle-free installed on cavities
  – qualified during integrated cavity tests in the Spoke Test Cryostat
SSR1 Tuner and resonance control

- **Prototype SSR1 tuner**
  - Design completed and one unit was prototyped
  - Successfully tested at 293K and cold temperature

- **Production SSR1 tuner**
  - Design completed
  - 1 out of 10 units was received and used for resonance control of SSR1 cavities
  - Active components for 1st cryomodule (9 electromechanical and 18 piezo actuators) were tested at cold temperature

- **Resonance control studies**
  - Requirements: microphonics <20 Hz
  - Good progress during cold tests at STC. ResControl algorithms, developed for ILC/ProjectX and LCLS II, successfully applied and requirements are nearly achieved.
Lab 2 cleanroom is a qualified facility for SRF activities: SSR1 string assembly
SSR1 cavities string assembly

Currently working on the cavity string assembly in the Lab2 cleanroom

- All string assembly components were subject QC inspections
- Particle-free procedures were developed and validated by qualifying cavities
- Alignment is being performed using laser trackers
- Possible design improvements have been identified and collected
SSR1 cavities string assembly: preparation

Charge #2
SSR1 Cryomodule

Conceptual layout of PIP-II CMs

- Vacuum vessel
- Dressed cavity
- 5 K Line
- Coupler
- 2-Phase He pipe
- Thermal shield 35-50K
- Support post
- Strong-back

SSR1 CM cross section
SSR1 Cryomodule: design maturity

- SSR1 Cavity String assembly
  - Design: completed
  - Procurement: completed
  - Assembly is ongoing
    - Completion expected by Dec 21, 2018

- SSR1 Coldmass
  - Design: completed
  - Procurement: ongoing

- SSR1 Top cryomodule assembly
  - Design: ready for FDR
  - Transportation tooling: in progress
  - Procurement: ongoing
  - Expected CM completion date
    - May 2019
  - Testing at PIP2IT
SSR1 CM assembly sequence

Procedures for the final CM integration are currently being developed
SSR1 CM Documentation

• Documents revision controlled in Teamcenter:
  – FRS, TRS and ICD
  – 2D drawings and 3D models
  – Reports of design reviews
  – P&ID was created and constantly updated
  – Piping engineering note: ready for final review (pre-approval)
  – Vacuum vessel engineering note: pre-approved
  – Procurement specifications
SSR1 cryomodules alignment

- **Laser trackers** will be used for the **Final alignment of cavities and solenoids** within the PIP-II alignment requirements, taking into account also the shifts due to cooldown.

- **HBCAM (Brandeis CAMera)** will be employed for monitoring the alignment of solenoids and cavities during transportation and cooldown.
SSR1 CM transportation tooling

Mixed approach: FEM – MultiBody. Assembly stiffness is computed through FE analysis (small components are simulated as lamped springs/masses) and then imported and combined in multi-body analysis: suspension system optimization, assembly dynamic characterization for transportation tooling design.

FEM: 240 s

MB: 20 s
SSR2 Preliminary design

• Cavity
  – RF design optimization and structural design is ongoing together with our partners (integrated team)
  – PDR is planned in March 2019

• Coupler
  – RF and structural design is being developed incorporating lessons learned from SSR1 couplers experience

• Tuner
  – An evaluation to adapt SSR1 tuner design is ongoing

• Cryomodule
  – A conceptual model of the cryomodule is needed to check interfaces
ESH

- Project team is committed to construct PIP-II in a safe, environmentally respectful, and cost efficient manner that meets our stakeholder’s needs
- All activities will be in full compliance with Laboratory and DOE standards
  - Fermi ES&H Manual
    - Pressure vessel compliance (Cavity/CM warm&cold ops)
      - All SRF cavities must comply ES&H Manual Chapter 5031.6
      - Cryogenic lines must comply ASME B31.3 for Pressure Piping
  - Division/Area specific Hazards Analyses and Training
    - Cryogenics exposure (Cavity/CM Testing)
    - ODH (Cavity/CM Testing)
    - Chemical/Acids (Cavity processing at ANL, controlled by ANL)
    - Radiation (Cavity/CM testing)
    - Material Handling
Quality Management

– Quality control
  • Procurement Quality / Supplier Quality are addressed by written procurement specifications and vendor visits
  • Incoming inspections are planned for all components (graded approach)
  • Acceptance testing are planned for critical sub-assemblies and documented in the Fermilab Vector database
    – Operating procedures
    – Travelers
  • Discrepancy reports and dispositions managed in Vector are used to address corrective actions

– QA Expectations for Partners
  • Partners shall have same or equivalent QC plans
## Risk Management

<table>
<thead>
<tr>
<th>Risk Rank</th>
<th>Risk ID</th>
<th>Title</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>RT-121-02-003</td>
<td>Underestimate d resources for design optimization of SSR1 CM (1)</td>
<td>If the SSR1 CM (1) does not meet technical performance requirements during PIP2IT testing, then the module must be removed from the PIP2IT beamline and a repair strategy implemented that may include cold-mass disassembly which will jeopardize PIP2IT testing plans, CM assembly of the HB650 CM(1), and delay the final designs of the SSR2 CM.</td>
</tr>
<tr>
<td></td>
<td>RT-121-02-003-C</td>
<td>Underestimate d resources for design optimization of SSR2 CM (1)</td>
<td>If the SSR2 CM (1) does not meet technical performance requirements during PIP2IT testing, then the module must be removed from the PIP2IT beamline and a repair strategy implemented that may include cold-mass disassembly which will jeopardize PIP2IT testing plans and delay the final designs of the SSR2 CM.</td>
</tr>
</tbody>
</table>

**Risk Register**
Summary

– FRS and ICD are defined and traceable in Teamcenter
– Proto SSR1 CM
  • Results of Integrated tests of SSR1 cavity, coupler and tuner in the Spoke Test Cryostat meet/exceed the requirements
  • SSR1 cavity string assembly is currently being assembled in the cleanroom at Lab 2
    • Components and sub-assemblies for the final CM integration are in the procurement phase. Detailed assembly procedures and tooling are being developed.
– Proto SSR2 CM
  • Cavity design is ongoing
    • Lessons learned from SSR1 experience will be applied
– ESH and QA plans are in place
– Risks are understood and tracked in the risk register
Thank you for your attention

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