SSR1 cryomodule

Donato Passarelli
PIP-II Collaboration Meeting
9-10 November 2015
Outline

- SSR1 cryomodule for PXIE
  - Specifications and Goals
  - SSR1 String Assembly
    - Overall status of the design and procurements
    - Cavities
      - Mitigation of pressure sensitivity
      - Status of manufacturing
    - Couplers
    - Solenoids
    - Beam position monitors
    - Tuners
      - Qualification of main components in the Spoke Test Cryostat
      - Conclusions
Two SSR1 cryomodules will be part of the 800 MeV linear accelerator complex that Fermilab is planning to build in the framework of the Proton Improvement Plan-II (PIPII) project. The cavity string assembly of this cryomodule which constitutes the beam-line volume, contains *eight* superconducting Single Spoke Resonators type 1 (SSR1) with cold-end input couplers and four solenoids.
SSR1 Cryomodule: Functional Requirements Specification

This engineering document “325 MHz SSR1 CRYOMODULE, FRS, ED0001316” (available in Teamcenter) addresses the functional requirements of the PIP-II SSR1 cryomodule. It includes physical size limitations, cryogenic system requirements and operating temperature, instrumentation, cavity and lens sequence and alignment requirements, magnet current leads, and interfaces to interconnecting equipment and adjacent modules.

<table>
<thead>
<tr>
<th>General</th>
<th>SRF Cavities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical beam aperture, mm</td>
<td>Number, total</td>
</tr>
<tr>
<td>Overall length (flange-to-flange), m</td>
<td>Frequency, MHz</td>
</tr>
<tr>
<td>Overall width, m</td>
<td>$\beta$ geometric</td>
</tr>
<tr>
<td>Beamline height from the floor, m</td>
<td>Operating temperature, K</td>
</tr>
<tr>
<td>Cryomodule height (from floor), m</td>
<td>Operating mode</td>
</tr>
<tr>
<td>Ceiling height in the tunnel, m</td>
<td>Operating energy gain at $\beta=0.22$, MV/cavity</td>
</tr>
<tr>
<td>Maximum allowed heat load to 70 K, W</td>
<td>Coupler type – standard coaxial with cold part</td>
</tr>
<tr>
<td>Maximum allowed heat load to 5 K, W</td>
<td>impedance, $\Omega$</td>
</tr>
<tr>
<td>Maximum allowed heat load to 2 K, W</td>
<td>Coupler power rating, KW</td>
</tr>
<tr>
<td>Maximum number of lifetime thermal cycles</td>
<td></td>
</tr>
<tr>
<td>Intermediate thermal shield temperature, K</td>
<td></td>
</tr>
<tr>
<td>Thermal intercept temperatures, K</td>
<td></td>
</tr>
<tr>
<td>Cryo-system pressure stability at 2 K (RMS), mbar</td>
<td></td>
</tr>
<tr>
<td>Environmental contribution to internal field</td>
<td></td>
</tr>
<tr>
<td>Transverse cavity alignment error, mm RMS</td>
<td>Number, total</td>
</tr>
<tr>
<td>Angular cavity alignment error, mrad RMS</td>
<td>Number of plates per BPM</td>
</tr>
<tr>
<td>Transverse solenoid alignment error, mm RMS</td>
<td>Accuracy of electrical center with respect to the</td>
</tr>
<tr>
<td>Angular solenoid alignment error, mrad RMS</td>
<td>geometric center, mm</td>
</tr>
</tbody>
</table>

Solenoids

BPMs

Fermilab
Prototype SSR1 Cryomodule for PXIE

A prototype cryomodule is under design and development to achieve the goals of:

- **Validate design concepts** of new spoke cavity cryomodule
  - Room temperature strongback
  - Individual support posts to control axial motion
  - Conduction cooled magnet current leads
  - Single-window coaxial input coupler
  - Integral beam instrumentation
  - Determine the practicality of tuner access ports
  - Estimate heat loads

- **Gain experience** with the required alignment tolerances and check alignment stability during cooldown.

- **Minimize risk ahead of full PIP-II design** and production effort by gaining experience with strings of spoke cavities, solenoids, and beam instrumentation, e.g. cleanroom operations, final assembly in the vacuum vessel, shipping and handling, etc.
SSR1 cryomodule contains eight cavities and four solenoids in the following order:
C–S–C–C–S–C–S–C–S–C–C

- Warm aluminum strongback and individual supports for each magnet and cavity
- Fine segmentation: insulating vacuum and the cryogenic circuits are confined to an individual cryomodule
- All connections to the cryogenic, RF, and instrumentation systems are external to the vacuum vessel
Design of the prototype SSR1 Cryomodule

SSR1 cryomodule – Top assembly
Conceptual design: completed
Final design: ~80% completed

SSR1 coldmass
Conceptual design: completed
Final design: ~80% completed

SSR1 string assembly
Final design: 100% completed
Procurement: 100% completed
Assembling: completed in FY16
SSR1 String Assembly: design features

- Interconnection cavity-cavity
  - Edge-welded bellows assembly
  - Al-diamond seals
  - SiBr set screws
  - 316L stainless nuts and washers

- Interconnection cavity-magnet-BPM-cavity
  - Hydro-formed bellows assemblies
  - Al-diamond seals
  - SiBr set screws
  - 316L stainless nuts and washers
SSR1 String Assembly in cleanroom

Key aspects:
• Particles-free assembling in a cleanroom class 10
• Alignment of cavities (electric axis) and magnets (magnetic axis) with a datum.
• Handling of the string assembly (minimum deformations)

Tooling for assembling: ~80% available
SSR1 String Assembly: Beam-line vacuum

High vacuum level (< 5E-5 Torr) is needed inside the beam line volume before the introduction of liquid helium in less than 12 hours.

- Measurements (very conservative conditions)

- Vacuum simulation (best scenario)

The high-vacuum level at room temperature can be achieved pumping down by the beam ports only. Furthermore, simulations performed on the entire string with clean components show that the achievable pressure would be of 7E-8 Torr pumping from both ends.

High-vacuum Simulations and Measurements on the SSR1 Cryomodule Beam-line, D. Passarelli et al., Proceedings of SRF2015, Whistler, BC, Canada
SSR1 String Assembly: Alignment (in progress…)

Alignment specifications (ED0001316)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse cavity alignment error, mm RMS</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Angular cavity alignment error, mrad RMS</td>
<td>≤10</td>
</tr>
<tr>
<td>Transverse solenoid alignment error, mm RMS</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Angular solenoid alignment error, mrad RMS</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

Estimation of cavities and solenoids misalignments due to the cooldown (293K --> 2K)

Referencing the electric axis of the cavity to external fiducials (beadpull + optical measurements + laser tracker). Error: ~ ±150µm

The positioning of the components in the string assembly will be defined starting from these results…
SSR1 String Assembly: components available

All components of the SSR1 string assembly were ordered and most of them are received.

- Jacketed SSR1 cavities (4 Type-A, 4 Type-B)
- 4 Solenoids
- 4 BPMs
- Production Couplers will arrive in mid-December
- All Hardware and Seals
- Interconnecting Bellows
- Warm-end transitions and gate valves
- Tooling
Other cryomodule components received as of today.

- Vacuum vessel
- Support Posts
- Prototype Tuner mechanism
- Strong-back
SSR1 Cavities: requirements

Table 1: Cavity operational and test requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF resonant frequency</td>
<td>325 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>±20 Hz</td>
</tr>
<tr>
<td>Operating accelerating gradient ($E_{acc}$)</td>
<td>12 MV/m</td>
</tr>
<tr>
<td>Quality factor ($Q_0$) at $E_{acc}$</td>
<td>&gt; 5 \times 10^{9}</td>
</tr>
<tr>
<td>Operating gain per cavity</td>
<td>2 MeV</td>
</tr>
<tr>
<td>Maximum power dissipation at 2 K</td>
<td>5 W</td>
</tr>
<tr>
<td>Sensitivity to He pressure fluctuations</td>
<td>&lt; 25 Hz/Torr</td>
</tr>
<tr>
<td>Field flatness</td>
<td>±10%</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>1.8 ± 2.1 K</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>16 ÷ 41 mbar (differential)</td>
</tr>
<tr>
<td>Maximum allowable working pressure</td>
<td>2 bar at 293 K, 4 bar at 2 K</td>
</tr>
<tr>
<td>RF power input per cavity</td>
<td>6 kW (CW, operating)</td>
</tr>
<tr>
<td>Max Leak Rate (room temp)</td>
<td>&lt; 10^{-10} atm \cdot cc/s</td>
</tr>
</tbody>
</table>

Teamcenter document numbers ED0001317
SSR1 Cavities: pressure sensitivity

The jacketed SSR1 cavities were designed to have very low sensitivity to helium pressure fluctuations (microphonics). We physically coupled the Nb cavity and the helium vessel such that we obtain a combination of cavity walls deformations \((x_1 + x_2)\) and \((x_3 + x_4)\) giving a \(df/dp = 0\).

Self-compensated system --> Passive compensation
No active control to mitigate the pressure fluctuations

<table>
<thead>
<tr>
<th>df/dp [Hz/Torr]</th>
<th>S106</th>
<th>S107</th>
<th>S108</th>
<th>S109</th>
<th>S110</th>
<th>S111</th>
<th>S112</th>
<th>S113</th>
<th>S114</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare cavity</td>
<td>-564</td>
<td>-561</td>
<td>-553.5</td>
<td>-555.1</td>
<td>-568.8</td>
<td>-525.8</td>
<td>-524.6</td>
<td>-544.7</td>
<td>-557.2</td>
</tr>
<tr>
<td>Measured</td>
<td></td>
<td></td>
<td>-1.2</td>
<td>5.4</td>
<td>7.9</td>
<td>2.7</td>
<td>9.0</td>
<td>6.3</td>
<td>10</td>
</tr>
<tr>
<td>Fully integrated</td>
<td>4*</td>
<td>4</td>
<td>0*</td>
<td>2*</td>
<td>4*</td>
<td>2*</td>
<td>5*</td>
<td>3*</td>
<td>5*</td>
</tr>
</tbody>
</table>

* Not measured yet (best guess)
SSR1 Cavities: design features

Electromagnetic Design
• Shape optimization
• Multipacting analysis
• Higher order modes
• Kick analysis
• Multipole effect
• Pressure Sensitivity
• Lorentz force detuning

Mechanical Design
• Niobium shell design
• Vessel design
• Shape optimization
• Pressure Rating
• Stiffening and detuning
• Modal analysis
• Tuner Design

The parallel approach in performing RF/Mech analyses benefits the final design...
SSR1 Cavities: Status

Status as today

- All the ten bare cavities were qualified in VTS
- The transition ring (Nb-stainless steel) was added to all cavities
- 9 out of 10 SSR1 cavities were jacketed with the helium vessel
- QC inspections: visual, pressure test, leak check, CMM
- Inelastic tuning (target: 325MHz at 2K with the tuner engaged)
- Referencing the electric center to outside fiducials (in progress)

Next (starting in Dec. 15)

- BCP, HPR, installation of coupler (cold-end)
- Qualification of cavities dressed with coupler in STC
SSR1 Cavities from IUAC ($Q_0$ vs $E_{\text{acc}}$ @ 2K)

Two SSR1 cavities were received from IUAC (India) part of the Indian Institutions and Fermilab Collaboration (IIFC). The summary plot shows one IUAC cavity (S1F-IU-104, magenta) together with all Fermilab cavities tested so far.

Cold Tests of SSR1 Resonators Manufactured by IUAC for the Fermilab PIP-II Project, L. Ristori et. al, SRF15 Conference
SSR1 325MHz Coupler: Status

Design specifications
- Beam power gain per cavity (CW): ~2 kW.
- Maximum design power (PIP-II, 5 mA): ~30 kW.
- One ceramic window at room temperature.
- No external adjustment.
- Air cooled center conductor.

Prototype Couplers
Three prototype couplers successfully tested to 8.5 kW at room temperature.
One prototype coupler tested in STC at the maximum design power of 30 kW.

325 MHz coupler anatomy

Production couplers
There is some delay on the production couplers because the design was changed to address several issues.
All 10 production couplers (cold-ends) will arrive at Fermilab in mid-December.
They are needed for qualification of cavities in STC.

Status of 325 MHz Main Couplers for PXIE, S. Kazakov, Proceedings of LINAC2014, Geneva, Switzerland
SSR1 325MHz Coupler: prototypes

Warm Outer conductor
Electro-deposited bellows
(Cu-Ni layers)

Warm Inner conductor

Cold-end assembly

RF test stand

Test Stand for 325 MHz Power Couplers, S. Kazakov, Proceedings of LINAC2014, Geneva, Switzerland
The cold-end of the coupler will be assembled on the cavity in a cleanroom (Class 10) using a specific tool and procedure for a “particle-free installation”.

Unity coupler was replaced with prototype high-power coupler
SSR1 Solenoids

Specifications
Lens strength (T²·m) 4
Steering dipole strength (T·m) 2.5·10⁻³
Insertion length, max. (mm) 160
Ferromagnetic shielding NO
Magnetic field on Cavity, max. (μT) 0.5·Q₀ criterion
Transverse misalignment (mm) 0.5 RMS
Angular misalignment (mrad) 1 RMS

Prototype Solenoids
- Prototype lens’ cold mass procured and tested at 2 K
- The lens assembled and re-tested
- Position of magnetic axis was measured by the vendor and at Fermilab: ΔR < 0.2 mm; Δα < 0.7 mrad

Production Solenoids
- Four production lenses’ cold masses procured and tested at 4 K by the vendor.
- The lenses were also tested in the VTS (Fermilab) at 2 K.
- Excellent agreement between predicted and measured performances
SSR1 Beam Position Monitors

Production BPMs
The finished BPM assembly is comprised of the 316L stainless steel body, a 50 Ohm SMA weldable feedthrough, alumina pins and an electrode. ANL has fabricated 4 Beam Position Monitors (BPMs) and delivered to Fermilab. Electrical continuity checks, final thermal cycling and leak checking, and the post fabrication cleaning were performed at ANL.

Characterization
Linear response of the BPM anticipated by simulations using CST Particle Studio, to be confirmed by stretched-wire measurements. This method will also allow the location of the electrical center of the BPM with respect to external fiducials.

Fully Integrated Test in the Spoke Test Cryostat

The jacketed SSR1 cavity (S1H-NR-107) dressed with prototype coupler and tuner was tested in the Spoke Test Cryostat at 2K. The performance of the power coupler and the frequency-tuning system were tested making sure they didn't interfere or degrade the performance of the cavity.

Results:
- Design of coupler validated: Prototype successfully tested to maximum power 30 kW.
- Design of Tuner validated...
- Jacketed cavity exceeds the specifications...
Testing at STC: $Q_0$ vs. $E_{acc}$ curve (S1H-NR-107)

No $Q_0$ degradation compared to VTS results $\rightarrow$ Manufacturing process of the jacketed cavity validated.

**PIP-II specification:**

$Q_0 > 5 \times 10^9$ at $E_{acc} = 12$ MV/m

---

*Result of Cold Tests of the Fermilab SSR1 Cavities*, A. Sukhanov et al., *Proceedings of LINAC2014*, Geneva, Switzerland
Testing at STC: Cavity Pressure Sensitivity (@ 2K)

Pressure sensitivity measured with Tuner engaged (as in operating condition)

\[ \Delta F, \text{ Hz} \]

\[ L\text{He pressure, Torr} \]

| Measurements |
| Fit: \( \frac{dF}{dP} = 4.45 \) [Hz/Torr] |

**PIP-II specification**

\( \frac{df}{dp} \leq 25 \text{ Hz/Torr} \)

**Design procedure to minimize the pressure sensitivity of the jacketed cavity with tuner is validated.**

**Estimated at room temperature:**

\( \frac{df}{dp} = 4 \text{ Hz/Torr} \)

Multipacting was simulated in SSR1 cavities for PIP-II, the results of SSR1 simulations have been compared with experimental data and the agreement seems very good.

Simulation of Multipacting in SC Low Beta Cavities at FNAL, G. Romanov et al., Proceedings of IPAC 2014, Richmond, VA, USA
Multipacting Simulations of SSR2 Cavity at FNAL, P. Berrutti et al., Proceedings of NA-PAC 2013, Pasadena, CA, USA
SSR1 Tuner

Specification
- Fine tuning >1 kHz
- Coarse tuning > 135 kHz
- Made of SS316L

Double lever Tuner
- Well known technology
- Adjustable mechanical advantage
- Piezos and motor in series
- Piezos away from the beam
- Estimated efficiency and stiffness
- Respect of the following maximum forces at the actuating components:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stepper motor with gear box</td>
<td></td>
</tr>
<tr>
<td>Max force</td>
<td>1300 N</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1 μm</td>
</tr>
<tr>
<td>Piezo</td>
<td></td>
</tr>
<tr>
<td>Stroke ((x_F)) at 293 K</td>
<td>68 μm</td>
</tr>
<tr>
<td>Stroke ((x_F)) at 20 K</td>
<td>15 μm</td>
</tr>
<tr>
<td>Max operating force</td>
<td>2700 N</td>
</tr>
<tr>
<td>Min operating force</td>
<td>840 N</td>
</tr>
</tbody>
</table>

SSR1 Tuner: Testing

**Coarse tuning** 135 kHz measured
\[ \Delta f_c \geq 135 \text{kHz} \rightarrow x_{BPC} \geq 250 \mu m \]
Active compensation of uncertainty due to cooldown, preload the system

**Fine tuning** 2.5 kHz measured
\[ \Delta f_f \geq 1 \text{kHz} \rightarrow x_{BPF} \geq 1.85 \mu m \]
Actively compensate the frequency shifts due to microphonics

**Passive tuning** \(+4.5 \text{Hz/Torr measured} \)
\[ k_{pass} \geq 30 \text{ N/\mu m} \rightarrow \frac{df}{dp} \leq 25 \text{ Hz/Torr} \]
Passively minimize the pressure sensitivity of the cavity

- FE analyses to simulate the three operating conditions and verify the value of stiffness and efficiency...and Testing Results

---

Tuner mounted on a test stand for initial measurement at room temperature.

Installation of SSR1 cavity (S1H-NR-107) with tuner and coupler into the Spoke cavity Test Cryostat (STC) at Fermilab.

---

SSR1 Tuner: Testing

Studies of microphonics control of the SSR1 cavity have been carried out using this tuner mechanism.

**Performance of the Tuner mechanism for SSR1 Resonators During Fully Integrated Tests at Fermilab, D. Passarelli et. al., Proceedings of SRF2015, Whistler, Canada, THPB061**
Conclusions

• All the components of the “string assembly” were ordered and many of them are at Fermilab
• The design of main components was validated by testing the prototypes (Jacketed cavity, Coupler, Tuner, Solenoid…)
• The final design of the “Top Assembly” and “Coldmass” needs to be completed
• FY 2016 Goals:
  – Qualify all the components of the “String assembly”.
  – Install the entire “String assembly”.
  – Finalize the design of the “Coldmass” and tooling.
  – Advance the microphonics control…
  – Consolidate the Indian Collaboration (IIFC): SSR1 cavities.
Acknowledgements

The progress of these activity are possible thanks to…

– Mechanical group in TD
  • T. Nicol, Y. Orlov, M. Parise, D. Passarelli, L. Ristori

– RF group in TD
  • P. Berrutti, M. Hassan, I. Gonin, T. Khabiboulline, A. Lunin, S. Kazakov

– Cavity processing (FNAL, ANL)
  • A. Rowe, O. Pronitchev, M. Merio

– Testing activities (VTS, STC)
  • J. Ozelis, A. Grassellino, A. Sukhanov, O. Melnychuk

– Microphonics control group in TD
  • Y. Pischalnikov, W. Schappert, J. Holzbauer

– Technical Support provided by other divisions (AD, PPD, …)
– Indian Collaboration
спасибо

GRACIAS
ARIGATO
SHUKURIA
THANK YOU
BIYAN
BOLZIN
MERCI