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TEST RESULTS OF THE PROTOTYPE SSR1 CRYOMODULE FOR PIP-II AT FERMILAB*

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Abstract

A prototype cryomodule containing eight Single Spoke Resonators type-1 (SSR1) operating at 325 MHz and four superconducting focusing lenses has been successfully assembled and cold tested in the framework of PIP-II project at Fermilab. The performance of cavities and focusing lenses along with test results of other cryomodule's key parameters are presented in this contribution.

INTRODUCTION

The PIP-II project [1] has the scope to upgrade the existing Fermilab's accelerator complex to deliver the most intense high-energy beam of neutrinos for the international Deep Underground Neutrino Experiment at LBNF. It is based on a proton driver superconducting linac that composes of five different Superconducting Radio Frequency (SRF) cavity types: half wave resonator (HWR), 325 MHz single spoke resonators type 1 and type 2 (SSR1, SSR2), low-beta and high-beta 650 MHz elliptical 5-cell cavities (LB650, HB650). Significant contributions from international research institutions in India, United Kingdom, Italy, France and Poland are planned to provide expertise and capabilities in accelerator technologies to the project.

Positioned as the second cryomodule type in the linac, the two SSR1 cryomodules operate at a frequency of 325 MHz with continuous wave (CW) RF power and peak currents of 5 mA to accelerate H^- beam from 10 MeV to 32 MeV. The design of the prototype SSR1 cryomodule (SSR1 pCM) is based a novel concept developed at Fermilab [2, 3]. The fine segmentation was the chosen configuration for the insulating vacuum and the cryogenic circuits that in this case confined within the individual cryomodule and the only connection between modules being at the beam tube. All external connections to the cryogenic, RF, vacuum, beamline, and instrumentation systems are made of removable junctions at the cryomodule itself. To minimize the movement of the beamline components and ancillaries during cooldown and to facilitate the assembly, the coldmass and the beamline components are based on a full-length strongback that is designed to be maintained at room temperature. A High Temperature Thermal Shield (HTTS) and Low Temperature Thermal Source (LTTS), along with connections for intercepts are made available between the inner surface of the vacuum vessel and the 2K helium to reduce radiation and conduction heat transfer. The current PIP-II beam optics design requires that each SSR1 cryomodule contains four superconducting focusing lenses (solenoids) and eight identical SSR1 cavities [4–6], where each cavity is equipped with one high-power RF coupler [7–11] and one tuner [12–14]. One of the SSR1 cavities that is integrated into the prototype cryomodule was developed by our partners at Bhabha Atomic Research Centre (BARC) in India [15].

ASSEMBLY AND INSTALLATION

The assembly and quality controls of the cryomodule starting from string assembly in the cleanroom [16, 17] throughout coldmass and final assembly [18] were performed at Fermilab's facilities. The prototype SSR1 cryomodule shown in Fig. 1 was completed in December 2019 and, later, transported [19–22] and installed in the PIP2IT cryomodule test cave. An Interface Specification Document along with electronic travelers provided the necessary framework for the involved groups to understand their interface and to report results. Discussions with each group provided clear channels for communication to resolve any conflict. The installation and checkout activities successfully ended in early July 2020 making the CM ready for cooldown.

Figure 1: Prototype SSR1 cryomodule for PIP-II.

ACCEPTANCE CRITERIA

The ultimate goal of testing SSR1 pCM at PIP2IT is to demonstrate that the cryomodule can provide acceleration of H^- beam with parameters required by the PIP-II physics program: the cavities shall be tested up to 115% of their nominal gradient set in Table 1. A phased approach was used to test cavities of SSR1 pCM. For Phase-I the CM was tested with cavities operating at the required gradients for the 1st SSR1 cryomodule of PIP-II linac. For Phase-II cavities gradients were increased to the required values for the 2nd SSR1 CM of PIP-II. It is required that the intrinsic quality factor of the cavities (Q_0) is better than $8.2 \cdot 10^9$ both at Phase-I and Phase-II.

Also, it is of extreme importance to demonstrate the achievement of critical CM operation parameters such as structural soundness of all critical CM components after

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cooldown, beamline and insulating vacuum levels, alignment of cavities and focusing lenses, couplers and tuners performance, focusing lenses reaching maximum design field, microphonics and resonance control, static and dynamic heat loads of the CM.

Table 1: Phase-I and Phase-II Cavities Gradient, MV/m

Cavity	1	2	3	4	5	6	7	8
Phase-I	4.88	4.63	4.78	7.32	7.8	7.56	7.32	10
Phase-II	10	8.78	8.05	10	9.76	10	8.54	10

RESULTS FROM COLD TESTING

Cooldown

After the completion of safety operation reviews for cryogenics and RF systems, the cooldown of the high temperature thermal shield (HTTS) started on 20 July 2020. The cooldown rate was limited by constraining the maximum temperature gradient across the HTTS: ΔHTTS<50 K; minimum temperature and maximum temperature gradient on the strongback(SB): TSB>283 K, ΔTSB<5 K. The cooldown of the HTTS was stopped when its temperature was at 100-130 K because of a leak developing into the insulating vacuum as the inlet temperature of the HTTS dropped below 100 K. This has been attributed to a physical interference between the shrinking HTTS and the current leads (CL) of the focusing lenses at the 1st and 4th (last) CL ports. With HTTS temperature kept at 100–130 K, stable operation of the cryomodule has been achieved with insulation vacuum better than $3.3 \cdot 10^{-7}$ mbar. The cooldown of Low Temperature Thermal Source (LTTS) started on 28th of July and stable operation of LTTS was established at 8–10 K. On the 30th of July, we reached stable condition in the 2 K circuit. The strong back temperature stabilized at 268 K, 15 K below the minimum designed value.

Vacuum

Separate vacuum pumping stations provided evacuation of the beamline volume and the insulating space. Before cooldown the beamline vacuum achieved $3.3 \cdot 10^{-9}$ mbar that is better than the required $1 \cdot 10^{-6}$ mbar, as predicted in [23]. Insulation vacuum level was at $4 \cdot 10^{-7}$ mbar. After cooldown, with the aid of cryo-pumping beam line vacuum reached $4 \cdot 10^{-10}$ mbar, and insulation vacuum stabilized over the weeks at $1.3 \cdot 10^{-8}$ mbar.

Alignment

The double-ended metrology cameras H-BCAMs® [24] were integrated in the prototype SSR1 to monitor the position of cavities and focusing lenses. The alignment monitoring started right after the final alignment was completed using laser tracker technique, and it continued throughout transportation, cooldown and cold testing of the cryomodule. More details about the design solutions and measurements are available in [25, 26]. The total vertical and horizontal displacements measured during cooldown are within the values estimated by thermal-structural finite element analyses: 0 mm horizontal displacement, 1.2 mm vertical displacement. In conclusion, the alignment of cavities and focusing lenses was retained during assembly, transportation and cooldown within 0.5 mm RMS.

RF Checkouts of Cavities

We started by first monitoring the RF characteristics of the cavities at room temperature (RT), then performed an intermediate check at 4 K, and finally evaluated the cavities performance at 2 K after achieving a stable operation of SSR1 pCM. As soon as stable operation of SSR1 pCM at 2 K has been achieved we evaluated RF performance of cavities. This included the measurement of the resonant frequencies of the fundamental mode and the 1st high order mode, the loaded Q-factor, and the external Q-factor of the field probe. The RF performance of the cavities were found to be comparable to data collected during cold test of individual cavities in the Spoke Test Cryostat [6].

Tuners Performance

At the same time, we checked the tuner performance, measuring range and resolution of both slow (stepper motor) tuner and fast, piezo actuated tuner. We found range and resolution of tuners well within specified requirements and tuned all cavities to operating frequency of 325.000 MHz.

Focusing Lenses Performance

All 4 SSR1 focusing lenses were successfully tested individually and then as a unit. Solenoids and correctors were powered to 47 A and ±30 A, respectively. No quenches were detected during nominal magnet operations.

Phase-I Cavities Testing

Individual cavity testing included off-resonance coupler conditioning in pulsed mode with 2–16% duty cycle and then in CW mode; calibration of LLRF system; conditioning of multipactor (MP) in cavities; characterization of cavity performance, including maximum cavity gradient and field emission radiation, if present.

SSR1 cavities have three strong MP barriers in the range 4–7.5 MV/m. Average time spent to condition MP was 16 hours per cavity. At Phase-I testing, we limited maximum cavity field to operating gradient of the 1st SSR1 cryomodule of PIP-II linac, ranging from 4.88 MV/m to 10 MV/m, from first to last cavity downstream. All 8 cavities achieved Phase-I gradients (see Table 1) with 15% margin. 7 cavities out of 8 were free of radiation from field emission (FE), while one cavity (cavity 4) had mild FE radiation just above background level. Measured level of microphonics was less than 10 Hz.

PIP2IT Beam Commissioning

After completion of Phase-I testing, the prototype SSR1 cryomodule has been successfully used in beam commissioning of the PIP2IT linac, accelerating beam of H^- ions up to 17.5 MV/m, with peak current of 5 mA and pulses up to 550 µs. Typical sequence of operation of SSR1 pCM

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for beam acceleration consisted of turning ON individual cavities in Self-Excited Loop (SEL) mode; ramping up cavity gradient close to nominal operation level; fine-tuning and turning ON resonance control with piezo tuners; turning ON LLRF feedback for cavity field and phase in Generator Driven Resonator (GDR) mode; setting cavity gradient and phase to exact nominal operation values. Measurements and adjustments of absolute cavity phase with respect to beam were made to get optimal acceleration and beam parameters.

Phase-II Cavities Testing

At the end of PIP2IT beam commissioning, we performed testing and characterization of cavities to Phase-II gradients, corresponding to the 2nd SSR1 cryomodule of PIP-II linac. All 8 cavities achieved operating gradient of Phase-II. Out of 8 cavities only 2 (cavity 3 and 4) had field emission radiation. Measured level of microphonics was less than 10 Hz.

Heat Load Measurements

We measured the static heat load (SHL) of the SSR1 pCM by evaluating change in thermodynamic parameters (temperature and pressure) of Helium before and after Joule-Thomson (JT) valve, at fixed JT-valve position and taking into account vapor fraction in JT expansion. We found that total static heat load was 37 W. This compared well with estimated static load of 40–50 W for the temperature of the HTTS ranging within 100–130 K. For dynamic heat load (DHL) evaluation we measured change in liquid Helium mass flow before and after application of RF power to cavities. Using heater installed inside of the pCM liquid level instrumentation canister, we calibrated change in LHe mass flow vs power applied to heater. Heater calibration was performed few times in the time frame October 2020–April 2021. Conversion factors obtained with those calibrations were consistent from measurement to measurement with mean value equal to 24.2 ± 0.2 W/(g/s). Sequence of DHL measurements is illustrated in Fig. 2 for cavities powered at Phase-I gradient. Table 2 summarizes results heat load measurements

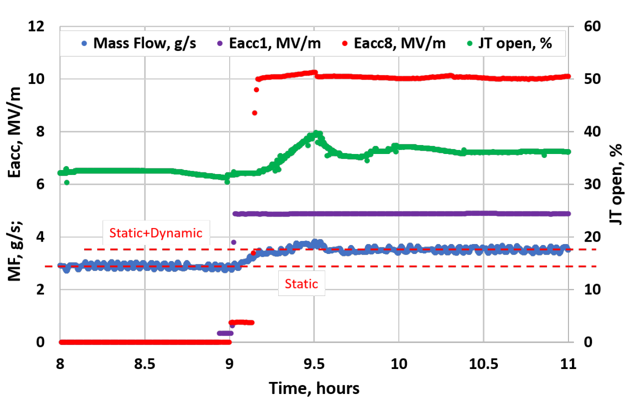

Figure 2: Dynamic heat load measurements.

CONCLUSIONS AND FUTURE WORK

The novel concept of cryomodule developed at Fermilab for the pSSR1 CM has been tested and many design choices fully validated. Lessons learned are collected and corrections to the design were made to improve performance. The assembly sequence of the CM, the onsite CM transportation phase, and the installation of the CM in the PIP2IT test cave were performed according to operating procedures with minor discrepancies that were resolved in a timely manner. The cooldown was performed following the constraints limiting the cooldown rate of the thermal shield and stable 2 K operation was reached within 10 days. However, the HTTS temperature was limited to 100–130K to avoid that a leak developed in the insulating vacuum. Also, the overall temperature of the strongback was 15 K below the design value of 283 K. A root cause analysis has been conducted and a plan to fix both issues during the next CM maintenance window (May-June 2021) was defined. After the repair, another cycle of cooldown-test-warmup will be conducted to check performances and validate the repairs.

Table 2: Summary of Heat Load Measurements

Parameter	Nominal condition	Current operating conditions	
		Estimated	Measured
HTTS	50–80 K	100–300 K	
SHL	26 W	40–50 W	37 W
DHL (Phase-I)	9 W	9 W	15 W
DHL (Phase-II)	15 W	15 W	38 W

The four focusing lenses and current leads passed all quality controls before and after the cooldown, and their performance in terms of magnetic fields met the project requirements.

All eight cavities were successfully powered up to Phase-I and Phase-II gradients and they were maintained on the resonant frequency of 325 MHz ±20 Hz using the tuners.

The measured SHL of the CM is aligned to the estimated value for the current operating conditions (HTTS at higher temperature than designed value), thus after the repair the SHL is expected to be at the nominal value of 26 W. The measured DHL of the CM for both Phase-I and Phase-II is considerably higher than estimated. Investigations and studies are ongoing to find an explanation and, possibly, a solution for the higher DHLs resulting in lower quality factor of the cavities (Q_0) than the required $Q_0 \geq 8.2 \cdot 10^9$ for both Phase-I and Phase-II.

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REFERENCES

[1] L. Merminga *et al.*, "The Proton Improvement Plan-II (PIP-II): Design, physics and technology advances, first tests", Invited submission to *Phys. Rev. Accel. Beams* (in preparation), 2021

[2] T.H. Nicol *et al.*, "SSR1 Cryomodule Design PXIE", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper WEPPD005, pp. 2504–2506.

[3] V. Roger *et al.*, "Design Update of the SSR1 Cryomodule for PIP-II Project", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2721–2723. doi:10.18429/JACoW-IPAC2018-WEPML019

[4] M.H. Awida *et al.*, "Development of Low β Single-Spoke Resonators for the Front End of the Proton Improvement Plan-II at Fermilab", *IEEE Trans. Nucl. Sci.*, vol. 64, no. 9, pp. 2450-2464, Sept. 2017. doi:10.1109/TNS.2017.2737560

[5] D. Passarelli *et al.*, "Preparation and Qualification of Jacketed SSR1 Cavities for String Assembly at Fermilab", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2714–2717. doi:10.18429/JACoW-IPAC2018-WEPML015

[6] A. I. Sukhanov *et al.*, "Characterization of SSR1 Cavities for PIP-II Linac", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 1120–1123. doi:10.18429/JACoW-SRF2019-THP090

[7] S. Kazakov *et al.*, "Latest Progress in Designs and Testings of PIP-II Power Couplers", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 263–266. doi:10.18429/JACoW-SRF2019-MOP080

[8] O.V. Pronitchev and S. Kazakov, "Mechanical Design of a High Power Coupler for the PIP-II 325 MHz SSR1 RF Cavity", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, paper THPB091, pp. 1354–1356.

[9] S. Kazakov *et al.*, "Testing of 325 MHz Couplers at Test Stand in Resonance Mode", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, paper THPB098, pp. 1376–1378.

[10] S. Kazakov *et al.*, "Status of 325 MHz Main Couplers for PXIE", in *Proc. LINAC'14*, Geneva, Switzerland, Aug.-Sep. 2014, paper THPP050, pp. 963–965.

[11] S. Kazakov *et al.*, "Main Coupler Design for Project X", in *Proc. LINAC'12*, Tel Aviv, Israel, Sep. 2012, paper TUPB053, pp. 594–596.

[12] J. P. Holzbauer *et al.*, "Testing of SSR1 Production Tuner for PIP-II", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2681–2683. doi:10.18429/JACoW-IPAC2018-WEPML005

[13] D. Passarelli *et al.*, "Performance of the Tuner Mechanism for SSR1 Resonators During Fully Integrated Tests at Fermilab", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, paper THPB061, pp. 1252–1256.

[14] D. Passarelli, "SSR1 Tuner Mechanism: Passive and Active Device", in *Proc. LINAC'14*, Geneva, Switzerland, Aug.-Sep. 2014, paper TUPP052, pp. 541–543.

[15] L. Ristori *et al.*, "Cold Tests of SSR1 Resonators Manufactured by IUAC for the Fermilab PIP-II Project", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, paper TUPB073, pp. 750–753

[16] D. Passarelli *et al.*, "Lessons Learned Assembling the SSR1 Cavities String for PIP-II", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 690–694. doi:10.18429/JACoW-SRF2019-TUP095

[17] M. Parise, "Preparation, processing, assembling and testing of spoke resonators: from SSR1 jacketed cavities to string assembly", Invited Talk at TESLA Technology Collaboration (TTC) Meeting, Milan, Italy, 2018. https://agenda.infn.it/contributionDisplay.py?contribId=53&sessionId=9&confId=13791

[18] D. Passarelli *et al.*, "Tooling Systems for the Assembly and Integration of the SSR1 Cryomodule for PIP-II Project at Fermilab", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2710–2713. doi:10.18429/JACoW-IPAC2018-WEPML014

[19] P. Neri *et al.*, "A multilevel finite element-multibody approach to design the suspension system for the road transportation of SSR1 cryomodule", *Transportation Engineering*, vol. 2, p. 100017, 2020. doi:10.1016/j.treng.2020.100017

[20] F. Bucchi *et al.*, "Experimental validation of the Finite Element-Multibody model of a cryomodule during road transportation", *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1038, p. 012063, 2020 doi:10.1088/1757-899X/1038/1/012063

[21] A Barnaba *et al.*, "Experimental modal analysis of SSR1 cryomodule for numerical model tuning and validation", *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1038, p. 012077, 2020 doi:10.1088/1757-899X/1038/1/012077

[22] P. Neri *et al.*, "Development of a Suspension System for the Road Transportation of Cryomodule SSR1 through a Multilevel Finite Element-Multibody Approach", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 297–301. doi:10.18429/JACoW-SRF2019-MOP089

[23] D. Passarelli *et al.*, "High-Vacuum Simulations and Measurements on the SSR1 Cryomodule Beam-Line", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, paper TUPB074, pp. 754–756.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB343

[24] Open Source Instruments, www.opensourceinstruments.com/HBCAM/

[25] S. Cheban *et al.*, "Alignment Monitoring System for the PIP-II Prototype SSR1 Cryomodule", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 332–334. doi:10.18429/JACoW-SRF2019-MOP102

[26] J. Bernardini *et al.*, "Computer vision techniques used to monitor the alignment of cavities and solenoids in the PIP-II prototype SSR1 cryomodule", presented at IPAC'21, Campinas, Brazil, 2021, unpublished.