Functional Requirement Specification for 325 MHz SSR1 Superconducting RF Cavities

Prepared by: Leonardo Ristori 325 MHz Cavities – Lead Engineer	Date: 6/22/12	**Organization** Fermilab TD/SRF	**Extension** 4401
Approved by: Vyacheslav Yakovlev SRF development department head	Date: 6/22/2012	**Organization** Fermilab TD/SRF	**Extension** 3888
Approved by: Thomas Nicol SSR1 Cryomodule – Lead Engineer	Date: 6-25-2012	**Organization** Fermilab TD/SRF	**Extension** 3441
Approved by: ~~Warren Schappert~~ Yuriy Pischalnikov TD – Test & Instrumentation department	Date: 6/22/12	**Organization** Fermilab TD/T&I	**Extension** 2906
Approved by: Valeri Lebedev PXIE – Lead Scientist	Date: 7/5/12	**Organization** Fermilab AD/Project X	**Extension** 2258
Approved by: R. Stanek PXIE – Lead Engineer	Date: 6/22/12	**Organization** Fermilab Directorate	**Extension** 3135

Revision History

Revision	Date	Revision Description
1	6/22/2012	Signed Initial Release

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I. SCOPE

The 325 MHz SSR1 spoke resonator cavities will be designed, manufactured, processed, tested, and assembled into cryomodules for Project X. This document covers the performance and test requirements for such cavities that consist of the following parts:

- Niobium Superconducting cavity
- Liquid Helium containment vessel
- Cavity-to-vessel coupling elements
- Active frequency-adjustment system (tuning system)

Introduction

Project X is a multi-MW proton accelerator facility based on an H^- linear accelerator using superconducting RF technology [1] [2] . The Project X 3 GeV CW linac employs 325 MHz spoke resonator cavities to accelerate 1mA of average beam current of H- in the energy range 10 – 160 MeV. The 325 MHz SSR1 ($\beta = 0.2$) cavities will accelerate the beam in the energy range of 10-32 MeV; followed by the SSR2 ($\beta = 0.47$) cavities accelerating the beam in the energy range 32-160 MeV. Project X will require 16 SSR1 cavities (2 cryomodules) and 44 SSR2 cavities (4 cryomodules).

We describe here the functional requirements of the 325 MHz SSR1 cavities necessary to meet the project goals.

The final design shall be determined by a review process based on the criteria given in this section, and the performance of prototype cavities.

SSR1 Cavity Design

Electro-magnetic design

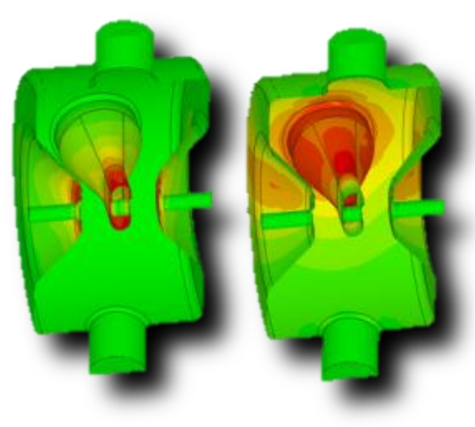

Figure 1: Electric fields (left) and magnetic fields (right) in SSR1

The SSR1 cavities designed and manufactured for HINS [3] (a 4 K pulsed linac) will be used for Project X. The shape of the resonators (see Figure 1:) was optimized to minimize the peak surface magnetic and electric fields to achieve the required gradient and minimize field emission and multipacting. The EM design parameters are summarized in Table 1.

Table 1. EM Cavity parameters

Parameter	Value
Frequency	325 MHz
Shape	Single Spoke Resonator
β_g, β_o	0.215, 0.22
$L_{eff} = 2*(\beta_o\lambda/2)$	203 mm
Iris Aperture	30 mm
Inside diameter	492 mm
Bandwidth	90 Hz
E_{pk}/E_{acc}	3.84
B_{pk}/E_{acc}	5.81 mT/(MV/m)
G	84 Ω
R/Q	242 Ω

Cavity Mechanical Design

The cavities are required to operate in CW regime in superfluid helium at a temperature to be determined but within the range of 1.8-2.1K. The maximum power dissipation for each cavity was calculated assuming a 40% additional power dissipation of other cryomodule components. Each cryomodule for these cavities shall dissipate no more than 50W average and peak power at 2K [4] .

The system of stiffeners present on the cavities shall be investigated and optimized if necessary to maintain mechanical stability, acceptable response to microphonics and Helium pressure fluctuations and overall ease of tuning under the different operating conditions of Project X.

In order to meet the requirements of the Fermilab ES&H Manual [6] [7] [8] several coupled thermal/structural analyses must be performed to assure a safe operation. These may include, but should not be limited to the following: elastic, elastic-plastic, collapse, buckling and ratcheting. The cavity mechanical design shall be consistent with suitable mounting and alignment schemes for cryomodule assembly [4] .

The cavities shall have appropriate interfaces with the helium vessel. Several different technologies are available for Niobium to Steel transition and the most appropriate should be selected on a cost-benefit basis.

The cavity operational and test requirements are summarized in Table 2.

Table 2. Cavity operational/test requirements

Parameter	Value
Max Leak Rate (room temp)	< 10^{-10} atm-cc/sec
Operating gain per cavity	2.0 MeV
Maximum Gain per cavity	2.4 MeV
Q_0	>5 x 10^9
Maximum power dissipation per cavity at 2 K	5 W
Sensitivity to He pressure fluctuations	< 25 Hz/Torr
Field Flatness	Within ±10%
Multipacting	none within ±10% of operating gradient
Operating temperature	1.8-2.1 K
Operating Pressure	16-41 mbar differential
MAWP	2 bar (RT), 4 bar (2K)
RF power input per cavity	6 kW (CW, operating)

Helium Vessel Design

The Helium vessel shall be fabricated from a non-magnetic stainless steel (e.g. 316L) designed to house a 2 K helium bath sufficient to remove up to 5 watts average dissipated power, with appropriately sized supply and return piping. It must meet the requirements of the Fermilab ES&H Manual for cryogenic pressure vessels and be rated at an MAWP (Maximum Allowable Working Pressure) of no less than 2 bar at room temperature and 4 bar at 2 K. Every effort should be made to minimize the weight and physical size of the helium vessel in all dimensions.

Tuning System

The presence and position of frequency tuners shall be determined before the cavity design is considered complete.

In order to accomplish the requirements for frequency range and resolution, the tuning systems for cavities of narrow bandwidths such as SSR1 typically integrate a coarse and a fine mechanism engaged in series. The first normally utilizes a stepper motor with large stroke capability and limited resolution, the latter usually contains piezo-electric actuators with limited stroke but virtually infinite resolution.

The coarse tuner is predominantly used to achieve consistently the resonant frequency during the cool-down operations. The range necessary to compensate for the cool-down uncertainties is estimated to be 50 kHz. In the event that a cavity must be detuned as a result of a malfunction, the coarse tuning system must be able to shift the frequency away from resonance by at least 100 bandwidths which equal to ≈10 kHz, so that the beam is not disturbed. The requirement on the range was set arbitrarily considering a safety margin of 2.7.

The requirement on the resolution of the coarse tuning system was set arbitrarily to a value that would allow operation in the event of a failure of the fine-tuning system. Based on other applications, it is believed that such resolution can be achieved with a coarse tuning system.

It is conservatively assumed that the coarse system cannot be operated during beam acceleration, it is thought that the vibration of a stepper motor may induce vibrations in the cavity severe enough to disrupt the operation.

Fine tuners shall be designed to compensate, at a minimum, the frequency shifts of the cavity induced by fluctuations of the helium bath pressure. The use of fine tuners will reduce considerably the hysteresis of the system by limiting the elements in motion during the tracking of the frequency.

A particular design effort shall be dedicated to facilitate the access to all actuating devices of the tuning system from access ports on the vacuum vessel. All actuating devices must be replaceable from the ports, either individually or as a whole cartridge.

Table 3. Tuning system requirements

Parameter	Value
Coarse frequency range	135 kHz
Coarse frequency resolution	20 Hz
Fine frequency range	1 kHz

Functional Specification Compliance

Features and availability at several facilities shall be required to ensure compliance with the cavity functional specification.

Cavity Inspection

The cavities' manufacturing conformance will be determined upon arrival at Fermilab. Four incoming inspections are anticipated: An initial visual inspection to ensure overall quality of cavity and shipment integrity, CMM measurement to determine the cavity has been manufactured according to the drawings, a room-temperature leak check, and a room temperature RF measurement of field flatness, and fundamental pass band frequencies.

Cavity Processing and Preparation

The cavity internal surface shall be prepared with a recipe which ensures with high probability that the Q_0, gradient and field emission levels will satisfy the requirements given in this document, with minimum cost and schedule impact. These cavities will receive bulk material removal by buffered chemical polishing in multiple steps, a hydrogen degasification bake in a vacuum oven, and inner surface cleaning via high pressure ultra pure water rinsing. Upon completion of the surface preparation, the cavities will be assembled for testing and qualification in a cleanroom environment.

Cavity Test

The performance of the cavities will be measured in terms of three figures of merit: Q_0 measured at the cavity operating gradient, maximum operating gradient, and field emission level at the operating gradient. These measurements will be obtained through two types of tests: a vertical test of the bare cavity in the Vertical Cavity Test Facility, and a horizontal test of the dressed cavity using high CW power (comparable to what the cavity would see in a beam line) in the Horizontal Test Facility.

The vertical test shall be used for initial qualification of the manufacturing and processing efficacy. Cavity performance shall reach at least 20% above the operational gradient and 20% above the operational Q_0 requirements to be considered qualified in the vertical test. Diagnostic instrumentation for quench location and field emission measurement shall be available for the vertical test.

If the bare cavity has an MAWP of less than 2 bar, the cavity will need to be protected from mechanical deformation due to vacuum pressure differential. This could be achieved by means of an exoskeleton constructed of Titanium.

The horizontal test shall be used as a test of the coupler, tuning system and dressed cavity assembly. Performance consistent with operational requirements shall be required for horizontal qualification of the cavity and peripherals. The horizontal test may be partially waived during the production stages of the project, if justified by consistent performance. The vertical test may also be partially waived during the production stages of the project if justified by consistent performance of bare cavities.

II. Project Interfaces

The cavity project shall interface to the cryomodule and RF projects at the beam pipe end flanges, cavity support locations, RF input and output coupler ports, and instrumentation feedthroughs. The cavities shall also include fiducial features that will aid in alignment.

III. Preliminary Safety Requirements

All designs shall be built to applicable FNAL engineering safety standards, and all cavity handling, processing and testing shall be performed according to applicable FNAL environmental safety and health requirements. All cavity and peripherals handling, processing and testing shall be subject to additional training and safety requirements specific to the relevant facilities.

IV. Quality Assurance Requirements

Electronic cavity travelers shall be developed documenting all stages of cavity fabrication, inspection, processing and tests. Each cavity will be identified univocally by a serial number appearing on the cavity (e.g. on one of the cavity flanges). A document summarizing the location, status and test results of all cavities shall be publicly accessible and continuously updated.

V. Reviews

Following the acceptable performance of prototype cavities, all elements that will be utilized on the production cavities (e.g. helium vessel, tuning system) will undergo design reviews prior to release for fabrication. The Project X/SRF management team will convene an appropriate review committee consisting of experts.

VI. References

[1] Project X Reference Design Report
http://projectx-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=776 .

[2] Project X retreat (November 2, 2010) summary
http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=784.

[3] Design, fabrication and testing of single spoke resonators at Fermilab – L. Ristori et al. – SRF 2009, Berlin, Germany.
http://accelconf.web.cern.ch/AccelConf/SRF2009/papers/thppo011.pdf

[4] 325 MHz Cryomodule Functional Requirements Specification, *PX doc-931*.
Draft SSR1 cryomodule functional requirements specification for PXIE

[5] Project X Optics v.3.7.4 (November 19, 2010)
http://indico.fnal.gov/getFile.py/access?contribId=1&resId=1&materialId=slides&confId=3740.

[6] Fermilab ES&H Manual Chapter 5031.6: Dressed Niobium SRF Cavity Pressure Safety
http://esh-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1097.

[7] Fermilab ES&H Manual Chapter 5031: Pressure Vessels
http://esh-docdb.fnal.gov/cgi-bin/ShowDocument?docid=456&version=4.

[8] Fermilab ES&H Manual Chapter 5031: Pressure Vessels
http://esh.fnal.gov/xms/FESHM.