Functional Requirement Specification for 650 MHz High Beta Superconducting dressed Cavity

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Revision History

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1	12/10/2010	Version 1
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I. SCOPE

The 650 MHz 5-cell elliptical 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
- 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 650 MHz elliptical 5-cell cavities to accelerate up to 2 mA of average beam current of H^- in the energy range 177 – 3000 MeV. The high beta $\beta_G = 0.90$ portion of the linac should accelerate from 480 to 3000 MeV. 120 $\beta_G = 0.90$ cavities shall be required for the project.

We describe the functional requirements of the 650 MHz cavities and facilities required to ensure the functional requirements are met.

650 MHz High Beta Cavity Design

The final cavity design shall be determined by a review process based on the criteria given in this section, and the performance of prototype cavities. The cavity RF and mechanical design parameters are summarized in Table 1; the cavity operational and test requirements are summarized in Table 2.

High beta Cavity RF design

The 650 MHz 5-cell elliptical cavities with geometric velocity factors $\beta_G = 0.90$ have been selected to optimize acceleration efficiency. The cavities are required to operate in CW mode in superfluid helium at a temperature to be determined but within the range 1.8-2.0K, with gradient (E_{acc}) of 17 MV/m, and unloaded quality factors, Q_0>2.0 x 10^{10} at 2K. The cell shape shall be designed to minimize the peak surface magnetic and electric fields, H_{peak} and E_{peak}, to achieve the required gradient and minimize field emission, and to minimize multipacting. The EM design parameters of high beta cavity are summarized in Table 1. In order to limit heat load per cryomodule and peak power at 2K [3] , we have a guideline for cavities in the current optics version [4] , of <25W per cavity for $\beta_G = 0.90$ cavities. The cavity beam line aperture shall be optimized within the constraints on field quality and beam losses. The cavity design shall include end groups with ports for RF power input and pick up couplers.

Table 1. Beta 0.9 Cavity EM parameters

Parameter	Value
Frequency	650 MHz
Shape, number of cells	Elliptical, 5 cells
Geometric beta β_g	0.90
$L_{eff} = 2*(\beta_g\lambda/2)$	1037.7 mm
Iris Aperture	100 mm
Bandwidth	45 Hz
E_{peak} at operating gradient	< 35 MV/m
B_{peak} at operating gradient	< 65 mT/(MV/m)
Cavity quality factor Q_0 at 2K	$>2.0*10^{10}$

Cavity Mechanical Design

The beam line aperture and cell shape shall be optimized to maintain mechanical stability and a high probability of effective surface processing. The cavity wall thickness and stiffening ring location shall be designed to satisfy FNAL engineering safety standards, acceptable response to microphonics and Lorentz-force detuning, and overall tune-ability. The presence and type of fast and/or slow tuners shall be determined before the cavity design is considered complete. The cavity mechanical design shall be consistent with suitable mounting and alignment schemes for cryomodule assembly. The end groups shall incorporate a suitable interface between the cavity and its helium vessel.

In order to meet the requirements of the Fermilab ES&H Manual [5] [6] [7] 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.

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. Beta 0.9 Cavity operational/test requirements

Parameter	Value
Operating node	CW

Max Leak Rate (room temp)	< 10^{-10} atm-cc/sec
Operating gain per cavity	17.7 MeV
Maximum Gain per cavity in VTS	> 21 MeV
Operating power dissipation per cavity at 2 K	< 25 W
Sensitivity to He pressure fluctuations	< 15 Hz/mbar (dressed cavity)
Field Flatness dressed cavity	> 90%
Operating temperature	2.0 K
Operating Pressure	30 mbar
MAWP	2 bar (RT), 4 bar (2K)
RF power input per cavity	up to 100 kW (CW, operating)
Cavity longitudinal stiffness	< 10^4 N/mm
Tuning sensitivity	> 180 kHz/mm

Helium Vessel Design

The Helium vessel shall be fabricated from titanium designed to house a 2 K helium bath sufficient to remove up to 25 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 bars 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, position and type 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 shall 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. Fine tuning system allows integration of active microphonics compensation.

The coarse tuner is predominantly used to achieve consistently the resonant frequency during cool-down operations and for preloading the piezo-electric actuator. 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 ≈45 kHz, so that the beam is not disturbed. For preloading of the piezo-electric actuator additional deformation of the cavity needed corresponding to 50 kHz frequency shift. Total frequency shift is 100 kHz. Cavity tuning sensitivity is 200 kHz/mm. The requirement on the tuning range considered a safety margin of 2.0. Coarse tuner should be able to change cavity length by 1 mm.

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 tuner frequency range	200 kHz
Coarse tuner frequency resolution	2 Hz
Fine tuner frequency range	500 Hz
Fine tuner frequency resolution	0.1 Hz

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, surface resistance R_s, 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 electropolishing or 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#2.

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.

The cavity will need to be protected from mechanical deformation due to vacuum pressure differential. This could be achieved by means of a reinforcing frame 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 (January 30, 2013) 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] 650 MHz Cryomodule Functional Requirements Specification, in preparation. http://accelconf.web.cern.ch/AccelConf/SRF2009/papers/thppo011.pdf

[4] 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.

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

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

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