Functional Requirement Specification

650 MHz Superconducting RF Cavities

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Revision History

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SCOPE

650 MHz cavities shall be designed, manufactured, processed, tested, and assembled into cryomodules for Project X. For the purposes of this project, cavities shall be defined to include magnetic shielding, a helium vessel, and any tuners and RF instrumentation required within the cryomodule. This document defines the programmatic need and the high-level functions the cavities, as designated, must fulfill.

1. 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 1mA of average beam current of H- in the energy range 160 – 3000 MeV. The 650 MHz portion of the linac is further split into two sections with two different geometric phase velocity factors: β_G = 0.61 for 160-520 MeV and β_G = 0.90 for 520-3000 MeV. Approximately 40 β_G = 0.61 and 150 β_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.

2. 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.

2.1 Cavity RF Design

The 650 MHz cavities shall be 5-cell elliptical cavities with two different geometric phase velocity factors, β_G = 0.61 and 0.90, selected to optimize acceleration efficiency with a minimum number of different cavity designs. The cavities are required to operate CW in superfluid helium at a temperature to be determined but within the range 1.8-2.1K, with gradients, E_{acc}, 16 or 19 MV/m, respectively, and unloaded quality factors, Q_0>1.7 x 10^{10} at 2K. The cell shape shall be designed to minimize the peak surface magnetic and electric fields, H_{peak}/E_{acc} and E_{peak}/E_{acc}, to achieve the required gradient and minimize field emission, and to minimize multipacting. Each cryomodule for these cavities shall dissipate no more than 250W average and peak power at 2K[3]; this leads to a guideline for cavities in the current optics version[4], using some assumptions about the power dissipation of other cryomodule components, of <35W per cavity for β_G = 0.61 cavities and <25W per cavity for β_G = 0.90 cavities. The cavity beamline aperture shall be optimized within the constraints on field quality and beam losses. The presence or absence of High Order Mode (HOM) extractors shall be determined before the design is complete. The cavity design shall include end groups with ports for RF power input and pick up

2.2 Cavity Mechanical Design

The beamline 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[5], acceptable response to microphonics and Lorentz-force detuning, and overall tunability. 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.

2.3 Cavity Peripherals Design

The cavities passing initial qualification shall be dressed in a helium vessel and outfitted with RF couplers, fast and slow tuners as needed, and magnetic shielding.

The helium vessel shall be designed to house a two-phase helium bath of sufficient volume and shape to cool up to average dissipated power described in section 2.1, with appropriately sized supply and return piping. It must be built to applicable FNAL engineering safety standards [6].

Input RF power couplers shall be designed to accelerate the beam and replace the energy dissipated in the cavity walls, providing 16 kW for $\beta_G = 0.61$ and 27 kW for $\beta_G = 0.90$ cavities. RF pickups shall be designed to measure transmitted power.

Slow tuners shall be mounted on the helium vessel, to control overall resonant frequency. Fast tuners shall be designed to compensate for microphonics, if determined to be needed.

The cavity magnetic shielding shall provide attenuation of ambient field to <10 mG during operation and test, to keep the residual resistance due to remanent magnetic field at the cavity below about 5 nOhm.

3. Functional Specification Compliance

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

3.1 Cavity Inspection [Table 1, to confirm items 1-5,10]

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, fundamental passband frequencies, and HOM notch frequency (if applicable). Optical inspection of the cavity interior surface using a high-resolution camera shall be performed, as needed, at various stages in cavity processing.

3.2 Cavity Processing and Preparation [Table 1, affects items 6-8,13,14]

The cavity internal surface shall be prepared with a recipe still to be optimized 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. The determined processing requirements are high-pressure water rinse with ultrapure water, and ultrasonic detergent cleaning. The still to be determined processing requirements will include one or more steps of electropolishing, buffered chemical polishing, and tumbling. Additional facilities required are: clean room facilities for assembly, a high-temperature vacuum furnace (650-800°C), a low-temperature baking stand (110-120°C) with vacuum pumping capability, and a tuning machine. Facilities for high-power coupler conditioning, tuner test and assembly, cavity dressing, and horizontal test preparation will also be needed. Storage and handling space will be needed for both bare and dressed cavities.

3.3 Cavity Test [Table 1, to confirm items 6-14]

The cavities' performance 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. Two test types are foreseen: a vertical test of the bare cavity using low CW power (up to 250 W) in the Vertical Cavity Test Facility, and a horizontal test of the dressed cavity using high CW power (comparable to what it would see in a beamline)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 10% 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 horizontal test shall be used as a test of the coupler, tuners, 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.

4. Project Interfaces

The cavity project shall interface to the cryomodule and RF projects at the cavity end flanges, cavity support locations, RF input and output, and instrumentation feedthroughs. The cavities shall include alignment features consistent with the overall alignment scheme which remains to be determined.

5. 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 [7]. All cavity and peripherals handling, processing and testing shall be subject to additional training and safety requirements specific to the relevant facilities.

6. Quality Assurance Requirements

A complete cavity traveler is to be developed documenting all stages of materials inspection, cavity fabrication, weld inspection, cavity processing steps and cavity tests. Cavity test results are to be recorded in the Project X cavity database.

7. Reviews

All designs will undergo review prior to release for fabrication. An appropriate review committee consisting of experts will be convened by the Project X/SRF management team.

Table 1: Cavity RF and mechanical design parameters

Requirement	Description	Value
1	frequency	650 MHz (2K)
2	shape, number of cells	elliptical, 5
3	geometric beta (β_G)	0.61, 0.90
4	iris minimum aperture	TBC: 83 mm (β_G =0.61), 100mm (β_G =0.90)
5	max leak rate	$<10^{-10}$ atm-cc/sec (room temperature)
6	gradient (E_{acc})	16 MV/m (β_G =0.61) or 19 MV/m (β_G =0.90) (operating); 5-25 MV/m (test)
7	Q_0	>1.7 x 10^{10} (operating), >0.8 x 10^{10} (test)
8	Dissipated power	<35W (β_G =0.61), <25W (β_G =0.90)
9	Microphonic control	df/dP<75 Hz/torr (2K); RF power overhead < 20 %
10	Field quality	TBD
11	HOMs	TBD
12	Residual resistance	<10 nΩ (vertical test)
13	Field emission	TBD (vertical test), TBD (horizontal test)
14	Multipacting	none measureable within ±10% of operating gradient

Table 2: Cavity operational/test requirements

Requirement	Description	Value
1	Operating temperature	TBD, in the range 1.8-2.1 K
2	Operating Pressure	TBD, in the range 16-41 mbar differential
3	MAWP	2 bar (room temperature), 4 bar(2K) internal to helium vessel; 1 bar differential external to helium vessel
4	RF power input per cavity	<16 kW (β_G =0.61), <27 kW (β_G =0.90) (CW, operating)

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9. References

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