Half-Wave Resonator Cryomodule
For Project X
Functional Requirements Specification

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Revision History

Revision	Date	Section No.	Revision Description
0	10/9/2011	All	Initial Draft
0.1	11/7/2011	All	Includes ANL's revision
1.0	02/13/2012	All	Includes transition to s-c-… optics, and alignment requirements

INTRODUCTION AND SCOPE

The goals and functional requirements for Project X are outlined in the Project X Functional Requirements document. The first superconducting cryomodule will contain a series of superconducting RF accelerating structures consisting of half-wave resonators (HWR) operating at 162.5 MHz, beam focusing elements and instrumentation and is intended to accelerate H- ions from 2.1 MeV to about 10 MeV. This specification addresses the Functional Requirements of the Project X HWR 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.

HWR CRYOMODULE Requirements

The cryomodule will contain cavities and couplers which will be designed to operate with a maximum forward power of 10 kW under any reflection condition. The RMS normalized bunch emittance at the CM exit should not exceed 0.25 mm mrad for each of 3 planes.

The beam optics design for Project X requires that the HW cryomodule contains 8 HW identical cavities and 8 focusing solenoids following in the following order: S C S C S C S C S C S C S C S C (beam direction). Two dipole correctors (horizontal and vertical) should be located inside each solenoid. A four-electrode beam button-type position monitor should be located downstream of each solenoid.

The cavity tuners have to be capable to support reliable cavity operation with 1 mA beam current, 4 kW forward power and helium pressure fluctuation up to 1 mbar (10σ of expected rms pressure fluctuation of 0.1 mbar.)

The intent is that this cryomodule has all external connections to the cryogenic, RF, and instrumentation systems made at removable junctions at the cryomodule itself. The only connection to beam line is the beam pipe itself which will be terminated by low particulate beam vacuum valves at both ends. It is desirable that some maintenance operations be possible “in situ”, namely the lid may be lifted above the vessel by 1 m inside the 4 m high tunnel by lowering the box and lifting the lid.
The General Requirements for the cryomodule are outlined in the table 1 below. Table 2 outlines the pressure requirements. Below table 2 the Cryomodule interface requirements are specified. This Functional Requirements Specification does not set exact sizes of the cryomodule and types of all its connections. However, all of these interfaces should be specified in a separate detailed technical specifications document at the beginning of the design process.

GENERAL REQUIREMENTS

General		
	Minimum beam aperture (ID), mm	33
	Overall module length; flange-to-flange, (target value), m	≤5.8
	Overall module width, (target value),m	≤1.6
	Beam line height from the floor, m	1.3
	Maximum cryomodule height from floor, (target value) m	~2
	The height in the tunnel available for the cryomodule maintenance, (target value), m	3.3
	Maximum allowed heat load to 70 K, (target),W	250
	Maximum allowed heat load to 4.5 K,(target), W	80
	Maximum allowed heat load to 2 K, (target), W	25
	Minimum number of lifetime thermal cycles	50
	Intermediate thermal shield temperature, K	45-80
	Thermal intercept temperatures, K	5 and 45-80
	Cryo-system pressure stability at 2 K, mbar	≤1
Cavities		
	Number	8
	Frequency, MHz	162.5
	β[i]	0.11
	Operating temperature, K	2.0
	Operating mode	CW
	Operating Accelerating Voltage at β=0.11, cavities 1 and 2, MV/cavity	1[ii]
	Operating Accelerating Voltage at β=0.11, cavities 3 through 9, MV/cavity	1.7
	Transverse alignment error (geometric center position, rms)[iii], mm	<±0.5
	Difference between electric and geometric centers, rms, mm	<±1
	Transverse alignment error, rms, mrad	≤±2.5
	Coupler type – standard coaxial with impedance	50 Ω
	Coupler Power Rating (full reflection)	10 kW
Solenoids		
	Number	8
	Operating temperature, K	2.0
	Current at maximum strength, A	≤100
	$\int B^2 dL$, $T^2 m$	2

	Transverse alignment error (magnetic center position), rms, mm	<±0.5
	Transverse alignment error (magnetic axis angle), rms, mrad	<±1[iv]
	Maximum fringe field at the cavity walls, (target) G	<10
	Each solenoid has independent power source	
Correctors		
	Number, total	8
	Number, per solenoid package	2
	Current, A	≤50
	Strength, T-m	0.0025[v]
BPMs		
	Number	8
	Type	button
	Number of plates	4

Table 1

SYSTEM PRESSURE RATINGS REQUIREMENTS

System	Warm MAWP (bar.a)	Cold MAWP (bar.a)
2 K circuit	2.0	2.5
5 K circuit	20.0	20.0
70 K piping	20.0	20.0
Insulating vacuum	1 atm external, vacuum inside	Na
Beam pipe outside cavities, includes beam position monitors and warm to cold transitions	1 atm external, vacuum inside	1 atm external, vacuum inside

Table 2

INTERFACES

The control of element alignment in a cooled down cryomodule is carried out through two optical ports located at the opposite sides of the cryomodule and having straight view along the axis. Each cavity and solenoid has to have 3 or better 4 fiducials distributed between these two ports. The cryomodule should also have fiducials mounted at its exterior for the cryomodule alignment relative to other elements of the accelerator. The exact location of the fiducials on the exterior of the HWR cryomodule can be defined at the time of the Conceptual Design Review.

The cryomodule assembly has interfaces to the following:

Bayonet connections for helium supply and return.
Cryogenic valve control system connections.
Pumping and pressure relief line connections.
Cryomodule positioning and alignment supports.
Beam tube connections terminated by a low particulate vacuum valve.
RF cables to the input couplers.
Instrumentation connectors on the vacuum shell.
Power supply cables for the solenoid and correctors connections.
Alignment fiducials on the vacuum shell with reference to cavity positions.

INSTRUMENTATION

Cavity and cryomodule instrumentation will include, but not be limited to the following. Internal wiring shall be of a material and size that minimizes heat load to the internal systems.

Beam position monitors.
Cavity field probes.
RF coupler temperature sensors.
Thermal shield temperature sensors.
Cavity helium vessel temperature sensors (externally mounted).
Cavity helium vessel heater (externally mounted).
Helium system pressure taps.
Helium level probes in the 2 K phase separator.
Helium temperature sensors in the 2 K phase separator.
Cavity vacuum monitors.
Insulating vacuum monitors.
Magnet Temperature sensors
Magnet quench protection sensors
Magnet quench heater instrumentation (as required)

ENGINEERING AND SAFETY STANDARDS

All vacuum vessels, pressure vessels, and piping systems will be designed, documented, and tested in accordance with the appropriate Fermilab ES&H Manual (FESHM) chapters. This includes the superconducting cavities and their associated helium vessels which must be designed, manufactured, and tested in accordance with FESHM chapter 5031.6, Dressed Niobium SRF Cavity Pressure Safety. Bellows shall be designed using the requirements of the Expansion Joint Manufacturers Association (EJMA). The cryomodule as a whole shall be designed to be free of frost and condensation when in operation in air with a dew point of 60 F.

QUALITY ASSURANCE

A complete cryomodule traveler is to be developed documenting all stages of materials inspection, cryomodule component fabrication, piping and weld inspection, cryomodule assembly, and test.

TECHNICAL REFERENCES

For purposes of calculating pressure relief requirements, conduction and radiation heat loads, etc., the following numbers should be used.

Worst-case heat flux to liquid helium temperature metal surfaces with loss of vacuum to air shall be assumed to be 4.0 W/cm^2.
Worst-case heat flux to liquid helium temperature surfaces covered by at least 5 layers of multi-layer insulation (MLI) shall be assumed to be 0.6 W/cm^2.
Thermal flux to the 2 K or 5 K level under a 70 K thermal shield is approximately 0.1 W/m^2 (1.36 W/m^2 black body).
Thermal flux to the 70 K thermal shield from room temperature vacuum vessel is approximately 1.5 W/m^2.

REFERENCES

1. Project X Functional Requirements Specification, Project-X-doc 658.
2. PXIE Functional Requirements Specification, Project-X-doc 980
3. MEBT Funtional Requirements Specification, Project-X-doc 938.
4. SSR1 Functional Requirements Specification, ,Project-X-doc 931
5. V. Lebedev, "Major Requirements to PXIE Optics and Design", http://projectx-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=930.

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[i] β is determined so that the maximum acceleration is achieved at this velocity
[ii] Beam dynamics limits the maximum voltage to approximately half of the nominal voltage
[iii] Cavity positioning and alignment is determined by requirement to minimize aperture limitations due to misalignments. Requirements to coincidence of geometric and electric center are not as strict.
[iv] 1 mrad error of solenoid alignment excites betatron oscillations of about 1.5 mm
[v] The corrector strength of 0.0025 T m excites betatron oscillations of about 10 mm