PIP-II 650 MHz β=0.61 Cryomodule Functional Requirements Specification

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Document Approval

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Revision History

Revision	Date of Release	Description of Change
0	11 Aug 2014	Initial Draft in DocDB
1	06 Nov 2014	Uploaded into Teamcenter - Changed maximum heat loads in cryomodule. 100W was 150W at 50k. 100W was 120W at 2k.
-	09/28/2015	Initial release
A	11/15/2017	The FRS scope and General Requirements Table updated
B	09/25/2018	Revised format. Merged individual FRS for cryomodule, cavity, coupler, and tuner into one FRS. Updated requirements based on new GRD and KPPs.

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1. Purpose

This Functional Requirements Specification (FRS) is intended to provide guidance to scientists, engineers, and designers for producing a Technical Design of the 650 MHz β=0.61 (LB650) cryomodule that will adequately achieve these requirements.

The FRS describes the functional and/or requested behavior of a system or components. The document typically outlines what is needed by the end user as well as the requirements and requested properties of inputs and outputs. The FRS specifies the functions that a system or component must perform and establishes consensus among stakeholders on what the system is expected to provide.

2. Scope

This document describes the Functional Requirements of the LB650 cryomodule that comprises the forth accelerating section of the CW RF PIP-II Superconducting Linear Accelerator (linac). The LB650 cryomodules shall accelerate and transport the beam coming from the SSR2 linac section. The LB650 Cryomodule Functional Requirements are dictated by the PIP-II beam requirements as found in the PIP-II Global Requirements Document (GRD) and Physics Requirements Document (PRD). Additional requirements are imposed by various applicable engineering standards and codes, and FNAL ES&H standards and policies.

3. Acronyms

EPDM	Engineering Process Document Management
FEM	Fermilab Engineering Manual
FESHM	Fermilab ES&H Manual
FRCM	Fermilab Radiological Control Manual
FRS	Functional Requirements Specification
GRD	Global Requirements Document
LB650	Low Beta 650 MHz (β=0.61)
HB650	High Beta 650 MHz (β=0.92)
L2	WBS Level 2
L3	WBS Level 3
MAWP	Maximum Allowable Working Pressure
PIP-II	Proton Improvement Plan II Project
PRD	Physics Requirements Document
RFQ	Radio Frequency Quadrupole
TC	Teamcenter
UHV	Ultra-High Vacuum
WBS	Work Breakdown Structure

4. Reference

#	Reference	Document #
1	PIP-II 650 MHz System Engineering Process Document Management (EPDM)	ED0001231
2	Fermilab Engineering Manual (FEM)	-
3	Fermilab Environmental Safety and Health Manual (FESHM)	-
4	Fermilab Radiological Control Manual (FRCM)	-
5	PIP-II Global Requirements Document	ED0001222
6	PIP-II Physics Requirements Document	TBD
7	PIP-II Cryogenic Heat Load Analysis	ED0008200

5. Key Assumptions

It is assumed that the LB650 cryomodule will accelerate a H- ion beam in pulsed mode at the pulsed current of 2 mA, pulse width of 0.54 ms, and repetition rate of 20 Hz. The LB650 cryomodules shall operate with continuous wave RF power and support peak currents of 10 mA chopped with arbitrary patterns to yield an average beam current of 2 mA. The LB650 cryomodules' operating mode frequency must match 650 MHz, which is the fourth harmonic of the RFQ frequency. There will be three helium cooling circuits provided from the PIP-II Cryogenic Plant, at temperatures of 2 K, 5 K and 50 K. The accelerating structures in the HB650 cryomodule shall operate at a temperature of 2.0 K.

6. Functional Requirements

Table 6-1. General Requirements

Requirement #	Requirement Statement
F-121.02.04.02-A001	The LB650 cryomodule shall accelerate H- ions.
F-121.02.04.02-A002	The LB650 cryomodule shall contain four identical accelerating cavities.
F-121.02.04.02-A003	The LB650 accelerating cavity should be designed to a geometrical beta of 0.61.
F-121.02.04.02-A004	The spacing between cavities in the LB650 cryomodule should be chosen to minimize the cryomodule length, while not compromising ability for cryomodule assembly.
F-121.02.04.02-A005	The LB650 cryomodule should contain RF interfaces capable of achieving nominal accelerating gradients in the cavities.
F-121.02.04.02-A006	The LB650 cryomodule should contain active frequency tuning systems integrated with accelerating cavities to meet the requirements for cavity frequency range and resolution.
F-121.02.04.02-A007	The LB650 cryomodule should conform to ambient magnetic field requirements on cavity surfaces.
F-121.02.04.02-A008	The LB650 cryomodules should have the ability for in-situ maintenance of frequency tuners' electromechanical components.
F-121.02.04.02-A009	The LB650 cryomodule components should be capable of a service life ≥ 40 years while exposed to ionizing radiation (100 mSv/hr) resulting from an average beam loss of 0.1 W/m.
F-121.02.04.02-A010	The LB650 cryomodule beamline vacuum should be better than 1×10^{-8} Pa at 2 K.
F-121.02.04.02-A011	The LB650 cryomodule beamline vacuum should be better than 1×10^{-5} Pa at room temperature.

Table 6-2. Cryogenic Requirements

Requirement #	Requirement Statement
F-121.02.04.02-B001	The LB650 cryomodule total static heat load at 2K shall be no more than the limit set forth in the PIP-II Cryogenic Heat Load Analysis, ED0008200.
F-121.02.04.02-B002	The LB650 cryomodule total static heat load at 5K shall be no more than the limit set forth in the PIP-II Cryogenic Heat Load Analysis, ED0008200.
F-121.02.04.02-B003	The LB650 cryomodule total static heat load at 50K shall be no more than the limit set forth in the PIP-II Cryogenic Heat Load Analysis, ED0008200.
F-121.02.04.02-B004	The LB650 cryomodule total dynamic heat load at 2K shall be no more than the limit set forth in the PIP-II Cryogenic Heat Load Analysis, ED0008200.
F-121.02.04.02-B005	The LB650 cryomodule shall include a heat exchanger which precools helium from approximately 4.5 K to 2 K.
F-121.02.04.02-B006	The LB650 cryomodule shall have a 2 K return circuit.
F-121.02.04.02-B007	The LB650 cryomodule shall have a 5 K supply and return circuit.
F-121.02.04.02-B008	The LB650 cryomodule shall be capable of cooling down cavities from 40 K to 4.5 K at a rate ≥ 2 K per minute.
F-121.02.04.02-B009	The LB650 cryomodule shall be capable of cooling down cavities from 175 K to 90 K at a rate ≥ 20 K per hour.
F-121.02.04.02-B010	The LB650 cryomodule shall have 5 K thermal intercepts available for support structures, input couplers, and to any other components if needed.
F-121.02.04.02-B011	The LB650 cryomodule shall have 50 K thermal intercepts available for support structures, input couplers, instrument wires, RF cables, and to any other components if needed.
F-121.02.04.02-B012	The LB650 cryomodule shall utilize bayonets for connection of all cryogenic circuits to the cryo-distribution system.
F-121.02.04.02-B013	The LB650 cryomodule shall be designed for a maximum number of 50 thermal cycles during its lifetime.
F-121.02.04.02-B014	The LB650 cryomodule shall have remotely operated cryogenic control valves.

Table 6-3. Instrumentation Requirements

Requirement #	Requirement Statement
F-121.02.04.02-C001	The LB650 cryomodule internal wiring shall be of a material and size that minimizes heat load to the internal systems.
F-121.02.04.02-C002	The LB650 cryomodule shall have thermometry to allow for monitoring and control under all expected operational scenarios.
F-121.02.04.02-C003	The LB650 cryomodule shall have pressure instrumentation to allow for monitoring and control under all expected operational scenarios.
F-121.02.04.02-C004	The LB650 cryomodule shall have vacuum instrumentation to allow for monitoring and control under all expected operational scenarios.
F-121.02.04.02-C005	The LB650 cryomodule shall have cryogen level instrumentation to allow for monitoring and control under all expected operational scenarios.
F-121.02.04.02-C006	The LB650 cryomodule shall have internal magnetic field probes to allow for monitoring and control under all expected operational scenarios.
F-121.02.04.02-C007	The LB650 cryomodule shall have cavity diagnostics to allow for monitoring and control under all expected operational scenarios.
F-121.02.04.02-C008	The LB650 cryomodule shall have input coupler diagnostics to allow for monitoring and control under all expected operational scenarios.

Table 6-4. Mechanical Requirements

Requirement #	Requirement Statement
F-121.02.04.02-D001	The LB650 cryomodule shall have a particle free vacuum gate valve at the beamline ends.
F-121.02.04.02-D002	The LB650 cryomodule beamline environment shall be classified as an UHV and low particulate region.
F-121.02.04.02-D003	The LB650 cryomodule insulating vacuum level when warm shall be $5x10^{-3}$ Pa before cooldown.
F-121.02.04.02-D004	The LB650 cryomodule assembly shall support beam line elements alignment procedure to provide proper beam steering and to meet the beam dynamic requirements
F-121.02.04.02-D005	The LB650 cryomodule shall have a support structure with required adjustability which will allow for positioning and alignment of accelerating structures, including alignment fiducials referenced to these structures.
F-121.02.04.02-D006	The LB650 cryomodule accelerating structures shall be equipped with targets linked to fiducials installed on the vacuum vessel.
F-121.02.04.02-D007	The LB650 cryomodule shall have ability for in-situ monitoring of the absolute locations and angular misalignments of accelerating structures.
F-121.02.04.02-D008	The LB650 cryomodule shall have relief ports with sufficient relief capacity for cavity and other potential trapped volume circuits, in accordance with FESHM guidelines.
F-121.02.04.02-D009	The LB650 cryomodule shall be able to be transported, handled, and installed in the PIP2IT enclosure utilizing the existing PIP2IT crane infrastructure with the static cribbing and adjustable support stands, and fitting within the allowable space.
F-121.02.04.02-D010	The LB650 cryomodule shall be able to be transported, handled, and installed in the PIP-II Linac enclosure utilizing the planned crane infrastructure and the cryomodule tunnel transport system, and fitting within the allowable space
F-121.02.04.02-D011	The LB650 cryomodule shall be able to be transported in a custom shipping frame from CEA-Saclay in France to Fermilab.
F-121.02.04.02-D012	The LB650 cryomodule shall have pneumatically actuated control valves
F-121.02.04.02-D013	The LB650 cryomodule shall have a vacuum relief for relieving the insulating vacuum space, in accordance with FESHM guidelines.
F-121.02.04.02-D014	The LB650 cryomodule shall be designed to withstand overseas transportation.
F-121.02.04.02-D015	The LB650 2 K circuit shall have a warm MAWP of 2.05 bar absolute.
F-121.02.04.02-D016	The LB650 2 K circuit shall have a cold MAWP of 4.10 bar absolute.
F-121.02.04.02-D017	The LB650 2 K positive pressure piping circuit shall have a MAWP of 20 bar absolute.
F-121.02.04.02-D018	The LB650 5 K circuit shall have a MAWP of 20 bar absolute
F-121.02.04.02-D019	Any other cryogenic circuit in LB650 shall have a MAWP of 20 bar absolute.
F-121.02.04.02-D020	The LB650 insulating vacuum shall have a MAWP of 1 bar absolute external, vacuum inside.
F-121.02.04.02-D021	The LB650 beam pipe, outside of the cavities, including the beam position monitors and warm to cold transitions shall have a MAWP of 1 bar absolute external, vacuum inside.

Table 6-5. Cavity Requirements

Requirement #	Requirement Statement
F-121.02.04.02-E001	The LB650 cavity inner shape shall be optimized to minimize the peak surface magnetic and electric fields to achieve the required gradient, and to minimize field emission and multipacting effects.
F-121.02.04.02-E002	The LB650 cavity mechanical design shall be optimized to maintain mechanical stability, acceptable response to microphonics, helium pressure fluctuations, and Lorentz Force Detuning (LFD), under all expected operational scenarios.
F-121.02.04.02-E003	The LB650 cavity Helium vessel shall be fabricated from a non-magnetic metal material.
F-121.02.04.02-E004	The LB650 cavity shall integrate coarse and fine frequency tuning mechanisms engaged in series.

Table 6-6. Coupler Requirements

Requirement #	Requirement Statement
F-121.02.04.02-F001	The LB650 input coupler shall operate at 650 MHz frequency.
F-121.02.04.02-F002	The LB650 input coupler shall have a single RF window.
F-121.02.04.02-F003	The LB650 input coupler shall have a fixed coupling with the cavity.
F-121.02.04.02-F004	The LB650 input coupler shall be able to support cavity operation at nominal gradient with 10% overhead.

Table 6-7. Tuner Requirements

Requirement #	Requirement Statement
F-121.02.04.02-G001	The LB650 coarse tuner shall protect cavities from plastic deformations during cryomodule assembly, transport, and operation.
F-121.02.04.02-G002	The LB650 coarse tuner mechanism shall be fabricated from a non-magnetic stainless steel.
F-121.02.04.02-G003	The LB650 coarse tuner shall compensate cavity frequency uncertainties after a cool-down and provide detuning off resonance by at least 500 bandwidths.
F-121.02.04.02-G004	The LB650 fine tuner shall compensate the cumulative frequency shifts of the cavity induced by Lorentz forces, microphonics, and fluctuations of the helium bath pressure.

7. Safety Requirements

The system shall abide by all Fermilab ES&H (FESHM) and all Fermilab Radiological Control Manual (FRCM) requirements including but not limited to:

Pressure and Cryogenic Safety
• FESHM Chapter 5031 Pressure Vessels
• FESHM Chapter 5031.1 Piping Systems
• FESHM Chapter 5031.5 Low Pressure Vessels and Fluid Containment
• FESHM Chapter 5031.6 Dressed Niobium SRF Cavity Pressure Safety
• FESHM Chapter 5032 Cryogenic System Review
• FESHM Chapter 5033 Vacuum Vessel Safety
Electrical Safety
• FESHM Chapter 9110 Electrical Utilization Equipment Safety
• FESHM Chapter 9160 Low Voltage, High Current Power Distribution Systems
• FESHM Chapter 9190 Grounding Requirements for Electrical Distribution and Utilization Equipment
Radiation Safety
• FRCM Chapter 8 ALARA Management of Accelerator Radiation Shielding
• FRCM Chapter 10 Radiation Safety Interlock Systems
• FRCM Chapter 11 Environmental Radiation Monitoring and Control
General Safety
• FESHM Chapter 2000 Planning for Safe Operations

Any changes in the applicability or adherence to these standards and requirements require the approval and authorization of the PIP-II Technical Director or designee.

In addition, the following codes and standards in their latest edition shall be applied to the engineering, design, fabrication, assembly and tests of the given system:

ASME B31.3 Process
ASME Boiler and Pressure Vessel Code (BPVC)
CGA S-1.3 Pressure Relief Standards
NFPA 70 – National Electrical Code
IEC Standards for Electrical Components

In cases where International Codes and Standards are used the system shall follow FESHM Chapter 2110 Ensuring Equivalent Safety Performance when Using International Codes and Standards and requires the approval and authorization of the PIP-II Technical Director or designee.