Fermi National Accelerator Laboratory

Fermilab

PIP-II Low Level RF
Functional Requirements Specification

Document number: ED0004194, Rev. A

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U.S. DEPARTMENT OF ENERGY | Office of Science

Document Approval

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Revision History

Revision	Date of Release	Description of Change
A		Initial Release

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1. Purpose

An FRS describes the project needs and/or requested behavior of a system or component. 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

The primary responsibilities of the Low-Level RF system are to provide a global frequency and phase reference, to provide cavity field regulation, to provide resonance control and to provide control for generating the necessary beam structure and operational modes. The RF system must be highly linear, stable, and must support a large dynamic range with a low noise floor. Additional responsibilities are for RF equipment protection and interlocks and supporting cavity and cryomodule test stands.

3. Acronyms

FEM	Fermilab Engineering Manual
FESHM	Fermilab ES&H Manual
FRCM	Fermilab Radiological Control Manual
FRS	Functional Requirements Specification
GDR	Generator Driven Resonator
IF	Intermediate Frequency
L2	WBS Level 2
L3	WBS Level 3
LLRF	Low Level Radio Frequency
MPS	Machine Protection System
PIP-II	Proton Improvement Plan II Project
RF	Radio Frequency
SEL	Self-Excited Loop
TC	Teamcenter
WBS	Work Breakdown Structure

4. Reference

#	Reference	Document #

1	PIP-II Low Level RF Engineering Process Document Management (EPDM)	ED0004128
2	Fermilab Engineering Manual (FEM)	-
3	Fermilab Environmental Safety and Health Manual (FESHM)	-
4	Fermilab Radiological Control Manual (FRCM)	-

5. Key Assumptions

Accelerator Control System Core Services

- Alarms: The ability to view and display alarms available is required. An alarm server that interprets RF system alarm information in the context of operating mode is required to produce meaningful RF alarms.
- Global Timing/Events: The timing system is synchronized to the RF reference. This system then provides LLRF with event triggers and data synchronization markers.
- Data Archiving: Data archive capabilities are required to support fault analysis, component lifespan analysis, overall system performance, and system interoperability studies. Waveform archiving to provide a time history of waveform data (history buffers) collected by the low-level RF system is required. This data is synchronous with other instrument systems.
- Data Save and Restore: Data associated with a machine configuration must be saved and available for restore to reestablish the RF parameters for an accelerator operations configuration (e.g. 60 MeV beam operations and the various beam currents).
- The ability to periodically save and restore RF control parameters must be available either automatically or on-demand to recover the RF system after an LLRF system reset.
- RF High-Level Functionality Applications: Applications that consider the behavior of all the cavities as a system or its interaction with other systems such as the following notable examples are required.

  An application similar to Krest (CEBAF), which is a beam-based tool that ensures the cavities are operated on crest (beam phase is the same as the cavity phase) by performing cavity-by-cavity and zone-by-zone phasing is required. In the case of the PIP-II LINAC the program will need to be able to set the cavities at the appropriate phase off of crest to meet the beam dynamics needs.

  Applications similar to LEMi (LINAC Energy Management for the Injector) and LEM are required to set up the optics lattice and to distribute desired energy gain across a LINAC segment taking into account operational drive highs limitations, cryogenic heat load considerations, fast and slow energy lock cavity headroom requirements, cavity trip rate models, cavity operational state, etc.

RF performance analysis tools similar to the RF Fault Counter, Cavity Status/History, RF Analyzing Tool (RAT), and gradient calibration are required to maintain and improve operability of the RF system. These tools shall have access to and respond to the LLRF system reported statuses as necessary.

6. Functional Requirements

6.1. Operational Requirements

Requirement #	Requirement Statement
F-121.3.04-A001	The LLRF system shall provide quench detection and mitigation capabilities.
F-121.3.04-A002	The LLRF system shall provide for fast recovery after quenches.
F-121.3.04-A003	The LLRF system shall provide control, status and data acquisition capabilities through the accelerator control system.
F-121.3.04-A004	Data from the LLRF system shall be timestamped with its associated event.
F-121.3.04-A005	Status indicators for permits/inhibits, internal power, and communication links shall be available on system front panels.
F-121.3.04-A006	Test points for main voltage rails in the system shall be available on system front panels.
F-121.3.04-A007	The LLRF system shall provide RF synchronous clocks to the global accelerator timing system.
F-121.3.04-A008	The LLRF system shall provide distributed phase-locked reference signals at 1300 MHz (for instrumentation and support systems), 650 MHz, 325 MHz, and 162.5 MHz.
F-121.3.04-A009	The LLRF system shall provide resonance control for all accelerating cavities.
F-121.3.04-A010	The LLRF system shall interface with the global control system used in the rest of the accelerator.
F-121.3.04-A011	The LLRF system shall be capable of interfacing with multiple control systems for scripting and expert studies.
F-121.3.04-A012	The LLRF system shall control/drive the stepper motor and piezoelectric cavity frequency tuners.
F-121.3.04-A013	The LLRF system shall allow for driving the Piezo amplifiers from local inputs to the amplifiers.
F-121.3.04-A014	The LLRF system shall provide RF alarm flags to the global control system, including, but not limited to, forward power fault, cavity gradient fault, and power sum fault.
F-121.3.04-A015	The LLRF system shall provide forward power, reverse power, and cavity gradient waveform history, pre and post trigger, with a 1μs or better resolution, upon receiving a fault trigger request from the clock/event system.
F-121.3.04-A016	The LLRF system shall be capable of retrieving setting history from the global control system upon power failure or system reboot.
F-121.3.04-A017	A testing suite shall be developed for board verification and debug.
F-121.3.04-A018	The LLRF system shall support a Self-Excited Loop (SEL) and a Generator Driven Resonator (GDR) mode.
F-121.3.04-A019	The LLRF on-board controller shall be capable of handling beam-based feedback control.

F-121.3.04-A020	The LLRF system shall be capable of limiting the output power to the amplifier using internally-set limits.
F-121.3.04-A021	The LLRF system shall be capable of automatically switching in and out of GDR mode .
F-121.3.04-A022	The LLRF system shall provide amplifier linearization and corrections using internal settings.

6.2. Physical Requirements

Requirement #	Requirement Statement
F-121.3.04-B001	The LLRF system's equipment, shall be designed to be installed in standard 19" wide racks, except where specialized equipment makes this approach impossible.
F-121.3.04-B002	The LLRF system includes a Master Oscillator and Reference Line system that shall be located along the gallery wall closest to the tunnel.
F-121.3.04-B003	All LLRF RF cables shall be selected based on performance characteristics at 1.3 GHz.
F-121.3.04-B004	All LLRF system RF signal runs shall be designed to be as short as reasonably possible.

6.3. Performance

Requirement #	Requirement Statement
F-121.3.04-C001	The LLRF system shall be designed for CW RF with pulsed beam operation.
F-121.3.04-C002	The LLRF system shall support pulsed RF for test stand and conditioning operations.
F-121.3.04-C003	The LLRF system shall measure the RF gradient and phase in each accelerating cavity with an accuracy necessary to meet the required beam parameters.
F-121.3.04-C004	The LLRF system shall provide amplitude and phase control of the RF field in the accelerating cavities.
F-121.3.04-C005	The LLRF system shall meet the energy stability requirements of injection into the Booster to meet LBNF/DUNE requirements.
F-121.3.04-C006	The LLRF system shall compensate for beam loading.
F-121.3.04-C007	The LLRF system shall support cavity RF conditioning.
F-121.3.04-C008	The LLRF system internal chassis connections shall be designed to withstand normal transport and handling acceleration and loads.
F-121.3.04-C009	Performance and testing data shall be available in a database for all LLRF system equipment.
F-121.3.04-C010	All LLRF system non-trivial components shall have unique serial numbers.
F-121.3.04-C011	All LLRF system complex subsystem components shall have model, revision and design IDs on them (PCB boards, chassis).
F-121.3.04-C012	All LLRF system complex subsystem components shall have barcodes/QR codes (PCB boards, chassis).
F-121.3.04-C013	All LLRF system PCB boards with non-trivial components shall have an on-board method to store identification data.

F-121.3.04-C014	All LLRF system racks shall have environmental monitoring available for temperature and humidity.
F-121.3.04-C015	A LLRF system simulator-on-chip shall be available for diagnostic purposes.
F-121.3.04-C016	The LLRF system shall provide online diagnostic tests for the control loops to confirm correct operation.
F-121.3.04-C017	In the case of a fault, the LLRF system shall be able to handle a shutdown without damaging the machine or itself.
F-121.3.04-C018	The LLRF system support handling of different events from the timing/events system.

6.4. Accelerator Safety and Protection Requirements

Requirement #	**Requirement Statement**
F-121.3.04-D001	The RFPI subsystem shall communicate with the MPS to protect the machine.
F-121.3.04-D002	The RFPI subsystem shall communicate with the personnel safety system to protect personnel .
F-121.3.04-D003	The LLRF system shall protect itself as required using a dedicated RF interlocks system.
F-121.3.04-D004	All LLRF system power sources located on a chassis shall have recessed connections/sockets to minimize the risk of shorting or other electrical faults.
F-121.3.04-D005	The LLRF system shall provide circular buffered data for beam loss or other machine fault diagnostics.

7. Applicable Standards

UL61010 - Laboratory equipment
UL60950 - Computing/Telecommunication Equipment
ASHRAE - Datacenter Standards
IPC-JSTD-001 – Soldering
IPC2221 – PCB spacing and design
IPC-A-600 -- PCB acceptance and testing
IPC-A-610 -- Electronics assembly

8. 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 Piping
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.

Additional Safety Requirements that are not listed in the general list above shall be included in the Requirements table in the Functional Requirements section.