

# PIP-II RF Protection Interlocks (RFPI)

## Technical Requirements Specification

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Document number: ED0013970

## Document Approval

| <b>Signatures Required</b>                                       | <b>Date Approved</b> |
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| Stakeholder Reviews performed off-line using TRS Metadata sheets | Dataset in TC        |

## Revision History

| Revision | Date of Release | Description of Change      |
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| 01       | 10/22/2021      | Initial Release for Review |
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|          |                 |                            |

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## 1. SCOPE

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The RF Protection Interlocks (RFPI) system has three objectives in the PIP-II linear accelerator. The primary objective of the RFPI system is to protect the cryomodule and its RF components. The RFPI system monitors signals associated with the SSA-coupler-cavity system and inhibits the low-level RF drive under fault conditions. It provides the SSA permits. The second objective is to provide a status to the accelerator machine protection system (MPS). The third objective is to provide diagnostic information (waveforms and status bits) to the control system in real-time during operation of each SSA-Coupler-Cavity being monitored.

## 2. ACRONYMS, TERMS, AND DEFINITIONS

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|        |                                                    |
|--------|----------------------------------------------------|
| RFPI   | Radio Frequency Protection Interlocks              |
| MEBT   | Medium Energy Beam Transfer                        |
| LEBT   | Low Energy Beam Transfer                           |
| PIP-II | Proton Improvement Plan II Project                 |
| L2     | WBS Level 2                                        |
| L3     | WBS Level 3                                        |
| MPS    | Machine Protection System                          |
| LLRF   | Low Level RF                                       |
| EPICS  | Experimental Physics and Industrial Control System |
| FEP    | Field Emission Probe                               |
| SSA    | Solid State Amplifier                              |
| IOC    | Input Output Controller                            |
| Quench | Sudden loss of superconductivity                   |
| NIRP   | Non-ionizing Radiation Protection                  |
| He     | Helium                                             |
| PSS    | Personnel Safety System                            |

## 3. REFERENCED DOCUMENTS

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- [1] PIP-II Cryomodule Operational FMEA Summary, ED0011450
- [2] LLRF Resonance Control TRS, ED0013968
- [3] SSR2 Coupler TRS, ED0013795

## 4. ROLES AND RESPONSIBILITIES

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### 4.1. Author(s)

Responsible for TRS preparation, including layout, proper format, requirement identification, requirement verification expectations, requirement traceability, and additional descriptive detail, as appropriate. The author is expected to engage subject matter experts as needed to ensure technical content is appropriately assessed and captured. The author is also expected to identify all applicable stakeholders to their noted requirement(s). In some cases, the author can also have the role of the document Owner.

### 4.2. Owner

Primary stakeholder and responsible for identifying the goals, objectives, and roles/responsibilities pertaining to that document and for assuring activities/expectations are performed as described. This is typically the Level 3 Manager of the sub-system to which this TRS belongs. The document owner is responsible for maintaining document content, revisions, and updates. An Owner is considered a “Checker” in Teamcenter workflow release when they are not the document Author.

### 4.3. Reviewer

Technical Integration Office (TIO) reviewers are responsible for ensuring TRS format is consistent with project standards, the appropriate document owner/author/reviewer/approver have been identified, the appropriate review process was implemented, and the appropriate document release process is executed. The TIO reviewers are required to be aware that the TRS document exists and is maintained within the framework of the project Document Management and Control Procedure. A Reviewer is considered a “Checker” in the Teamcenter workflow release.

### 4.4. Approver

The L2 Manager will evaluate the basis for requirements definition, ensure that requirements are properly articulated, and ensure that they align with higher level requirements specifications, as applicable. The L2M will ensure that CAMs, associated engineering staff, and other Systems Managers are properly engaged and notified of the document’s technical implications. Only the System Manager responsible for the work product addressed in the specification is expected to provide approval. The Approver is an “Approver” in the Teamcenter workflow release.

### 4.5. Stakeholder

Each TRS includes a metadata sheet which lists each TRS requirement individually and assigns stakeholders to each. A stakeholder is a subject matter expert pertaining to the given requirement and/or has a direct stake in the requirement. Identified stakeholders are expected to be reviewers, ensuring accuracy and completeness, of requirements and content applicable to them and their associated scope of work. Stakeholder reviewers ensure a record of decision is made offline for accepting, rejecting, or modifying the requirement statement assigned to them within the TRS metadata sheet (included as a dataset in Teamcenter).

## 5. REQUIREMENTS

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### 5.1. System Definition

Background:

The interlock system responds to settings from the controls system by receiving trip setting levels.

- Alarms: The ability to view and display available alarms. An alarm server that interprets RFPI system alarm information in the context of operating mode to produce meaningful RFPI alarms.
- Data Archiving: Data archive capabilities like what is in existence (EPICS collaboration) now are required to support fault analysis, component lifespan analysis, overall system performance, and system interoperability studies (e.g., interactions between RF system and energy locks). Waveform archiving to provide a time history of waveform data (history buffers) collected by the RFPI system is required.
- Configuration Save and Restore: Data associated with a machine configuration must be saved and available for restore to the front-end computer in order to reestablish the RFPI parameters for a particular accelerator operations configuration (e.g. 60 MeV beam operations and the various beam currents).
- The ability to periodically save and restore RFPI control parameters must be available either automatically or on-demand in order to recover the RFPI system after a front-end computer reboot or RFPI system reset.

System Diagram

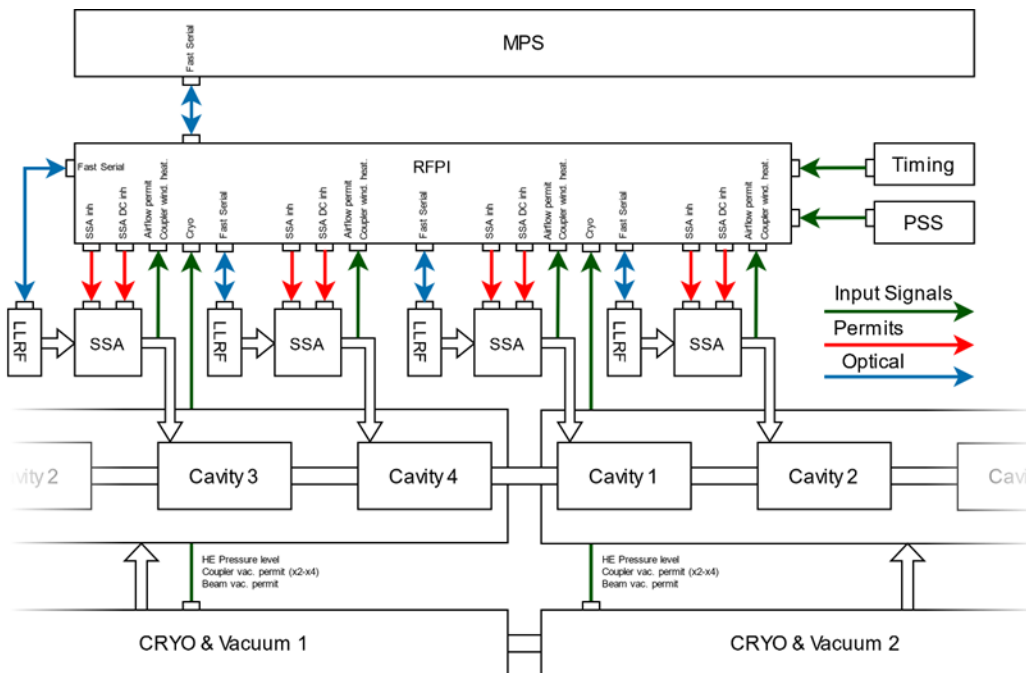


Figure 5.1: RFPI System Diagram

System architecture

The RFPI system diagram is shown in Figure 4.1. One RFPI system supports four Cavity/Couplers. This configuration matches the number cavity/couplers supported by an LLRF system, rather than matching the number of cavity/couplers within a given cryomodule. Therefore, the system diagram depicts a portion of connections to one cryomodule and another portion to a different cryomodule.

Figure 4.2 below shows how the various inputs, as well as outputs quantities are arranged based upon various accelerator systems.

| Signal Name                                        | Quantity                                   |
|----------------------------------------------------|--------------------------------------------|
| Field Emission Probe (FEP)                         | 1 per cavity/coupler                       |
| Coupler Bias Current (A)                           | 1 per cavity/coupler                       |
| Coupler Bias Voltage (V)                           | 1 per cavity/coupler                       |
| RF antenna (NIRP)                                  | 1 per cavity/coupler +<br>1 per CRYOMODULE |
| Cryo (He Pressure & Level) Permit                  | 1 per CRYOMODULE                           |
| Coupler Airflow Permit                             | 1 per cavity/coupler                       |
| Coupler Vacuum Permit                              | 1 per cavity/coupler                       |
| Beam Vacuum Permit                                 | 1 per CRYOMODULE                           |
| Personnel Safety Permit                            | 1 per cavity/coupler                       |
| Coupler Temperature Probe RTD 1                    | 1 per cavity/coupler                       |
| Coupler Temperature Probe RTD 2                    | 1 per cavity/coupler                       |
| LLRF Ready (RF level status, Ready status, quench) | 1 per cavity/coupler                       |
| SSA Ready                                          | 1 per cavity/coupler                       |
| SSA Permit Out                                     | 1 per cavity/coupler                       |
| SSA DC Permit Out                                  | 1 per cavity/coupler                       |
| LLRF Permit Out                                    | 1 per cavity/coupler                       |
| MPS Permit Out                                     | 1 per cavity/coupler                       |

**Figure 5.2: RFPI I/O Parameters for Permits**

There are three major systems where the RFPI will communicate to in order to provide outputs (and inputs). These systems are the Machine Protection System (MPS), Low Level RF system (LLRF) and the Solid-state amplifiers (SSA). The combination of inputs making up these output permits are shown in the functional diagram in Figure 4.3.



| Inputs to RFPI                       | Output Permits from RFPI (LB/HB) |            |               |     |
|--------------------------------------|----------------------------------|------------|---------------|-----|
|                                      | LLRF permit                      | SSA Permit | SSA_DC Permit | MPS |
| FEP                                  | x                                |            |               | x   |
| RF antenna (NIRP)                    | x                                | x          |               | x   |
| Personnel Safety Permit              | x                                | x          |               | x   |
| Vacuum Status                        | x                                | x          |               | x   |
| Coupler Vacuum Permit (Multipacting) |                                  |            |               | x   |
| He Level & Pressure (Cryo)           | x                                | x          |               | x   |
| Temperature Sensors (RTD 1& 2)       | x                                | x          |               | x   |
| Coupler Airflow Sensor               | x                                | x          |               | x   |
| HV Coupler Bias voltage              | x                                | x          |               | x   |
| HV Coupler Bias current              | x                                | x          |               | x   |
| SSA Ready                            | x                                |            |               | x   |

**Table 4.1: Functional Diagram**

### Software Controls

Table below shows the inputs that will be available for timing from the Control System needed for critical timing/communication such as for post mortem-analysis.

| Control | Function        | Document ID | Description |
|---------|-----------------|-------------|-------------|
| L-clock | Timing/Controls | ED0013498   | L-Clock TRS |
| A-clock | Timing/Controls | ED0013499   | A-Clock TRS |

**Table 4.2****5.2. Interface Definition**

- All external cable connections to the RFPI system shall be as per described in [ICD document number]

| <b>Source</b>                   | <b>Signal</b>            | <b>Function</b>                  | <b>Specifications</b>                          |
|---------------------------------|--------------------------|----------------------------------|------------------------------------------------|
| FEP                             | analog                   | limit for couple field emissions | TTL into 50 ohms                               |
| Stray RF Detection (NIRP)       | analog RF/162.5-1300 MHz | Limit for non-ionizing radiation | Sine, 0 dBm into 50 ohms                       |
| Personnel Safety Permit         | contact switch           | Personnel safety system permit   | Permit drops when metal contact switch is open |
| Vacuum Status                   | Broadband RF             | Vacuum permit                    | Permit drops when metal contact switch is open |
| Coupler Vacuum gauge            | contact switch           | Vacuum permit                    | Permit drops when metal contact switch is open |
| Cryogenics Status               | contact switch           | Cryogenics permit                | Permit drops when metal contact switch is open |
| Temperature Sensors (RTD 1 & 2) | Analog                   | Window temperature               | 0-10V                                          |
| Coupler Airflow Sensor          | contact switch           | Coupler airflow permit           | Permit drops when metal contact switch is open |
| HV Coupler Bias voltage         | analog                   | Limit for power supply levels    | 0-10V signal                                   |
| HV Coupler Bias current         | analog                   | Limit for power supply levels    | 0-10V signal                                   |
| SSA Ready                       | digital                  | HLLRF permit                     | TTL into 50 ohms                               |
| LLRF Status                     | digital                  | LLRF system permit               | High-speed serial link                         |

|                 |         |                                     |                        |
|-----------------|---------|-------------------------------------|------------------------|
| Forward Power   | digital | Limit for excessive forward power   | High-speed serial link |
| Reflected Power | digital | Limit for excessive reflected power | High-speed serial link |
| Cavity Quench   | digital | Quench detection                    | High-speed serial link |

Table 4.3 RFPI Inputs

| Destination | Signal         | Function | Specifications   |
|-------------|----------------|----------|------------------|
| SSA         | digital output | Permit   | TTL into 50 ohms |
| SSA DC      | digital output | Permit   | TTL into 50 ohms |
| LLRF System | digital output | Permit   | TTL into 50 ohms |
| MPS System  | digital output | Permit   | TTL into 50 ohms |

Table 4.4: RFPI Outputs

## 6. REQUIREMENTS

### 6.1. Performance

| Requirement #     | Requirement Statement                                                                                           |
|-------------------|-----------------------------------------------------------------------------------------------------------------|
| T- ED0013970-A001 | The RFPI system shall support signals with response time as fast as 100usec, such as FEPs.                      |
| T- ED0013970-A002 | The RFPI system shall support signals with response time on the order of 1 msec scale, such as beamline vacuum. |

|                   |                                                                                                                                                                                 |
|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| T- ED0013970-A003 | The RFPI system shall support signals with response time on the order of 1 second scale, such as coupler air flow.                                                              |
| T- ED0013970-A004 | The RFPI system shall receive input signals consisting quad fiber optic, high-speed serial links, analog, digital (TTL), contact switches, RF and RTD channels.                 |
| T- ED0013970-A005 | The RFPI system shall provide output signals in a digital (TTL) format                                                                                                          |
| T- ED0013970-A006 | One RFPI systems shall serve four LLRF systems                                                                                                                                  |
| T- ED0013970-A007 | Single RFPI systems shall be capable of communicating with one another via high speed data link.                                                                                |
| T- ED0013970-A008 | <ul style="list-style-type: none"> <li>• The RFPI system's RF inputs shall support:<br/>50 ohms input impedance</li> <li>• Input frequencies from 162.5MHz to 1.3GHz</li> </ul> |

## 6.2. Operational requirements

| Requirement #     | Requirement Statement                                                                                                                                                           |
|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| T- ED0013970-B001 | The RFPI shall have provision for expert masking of inputs.                                                                                                                     |
| T- ED0013970-B002 | RFPI inputs & outputs shall latch upon fault condition.                                                                                                                         |
| T- ED0013970-B003 | RFPI system shall be able to clear/reset faults upon operator request.                                                                                                          |
| T- ED0013970-B004 | The RFPI system shall provide post-mortem data to the control system including time stamp information and inputs leading to the fault information.                              |
| T- ED0013970-B005 | The RFPI system shall have trip limits settable and accessible remotely in an expert mode.                                                                                      |
| T- ED0013970-B006 | The trip limits for the RFPI system shall have save & restore features. If the RFPI system is rebooted, all trip limits and settings shall be automatically restored.           |
| T- ED0013970-B007 | The RFPI and LLRF systems shall have a high-speed serial link (bi-directional) between the two systems to pass critical information, such as RF level status and Quench status. |
| T- ED0013970-B008 | The RFPI system must have a watchdog circuit monitoring processes and inhibit RF on faults.                                                                                     |

### Physical Characteristics

| Requirement #     | Requirement Statement                                                                                                                                                                                                                                                                                                  |
|-------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| T- ED0013970-C001 | The RFPI hardware shall all be designed to be mounted in standard 19" wide racks based on EIA-310.                                                                                                                                                                                                                     |
| T- ED0013970-C002 | The hardware in total shall occupy a depth of no greater than 25", which includes the chassis as well as any possible connectors, adapters, attenuators and cable bend radius which may protrude from the back of the chassis. The chassis shall be able to be easily accessible for installation and troubleshooting. |
| T- ED0013970-C003 | All connectors to hardware shall be spaced apart such that connecting or disconnecting cables can be done with ease, and without having to disconnect more cables than necessary.                                                                                                                                      |
| T- ED0013970-C004 | The RFPI shall provide local reset capability at the rack, such as via a momentary push button switch.                                                                                                                                                                                                                 |
| T- ED0013970-C005 | The RFPI system shall provide LED indicators for at least critical items, such as power supply (on/off), Safety Permit (contact switch input), clock signals and the four output permits                                                                                                                               |

### Reliability, Maintainability, and Availability

| Requirement #     | Requirement Statement                                                                                                      |
|-------------------|----------------------------------------------------------------------------------------------------------------------------|
| T- ED0013970-D001 | All printed circuit boards (PCBs) shall meet IPC2221B standard. All wiring and chassis design shall meet UL61010 standard. |
| T- ED0013970-D002 | All RFPI system non-trivial components shall have unique serial numbers.                                                   |
| T- ED0013970-D003 | All RFPI system complex subsystem components shall have model, revision and design IDs on them (PCB boards, chassis).      |
| T- ED0013970-D004 | The RFPI system shall have sufficient spares.                                                                              |

### Environmental Conditions

| Requirement #     | Requirement Statement                                                                                           |
|-------------------|-----------------------------------------------------------------------------------------------------------------|
| T- ED0013970-E001 | All RFPI system hardware shall be able to operate over the temperature and humidity range of the PIP-II gallery |

### Transportability

| Requirement # | Requirement Statement |
|---------------|-----------------------|
|---------------|-----------------------|

|                   |                                                                                                                                   |
|-------------------|-----------------------------------------------------------------------------------------------------------------------------------|
| T- ED0013970-F001 | The RFPI system internal chassis connections shall be designed to withstand normal transport and handling acceleration and loads. |
| T- ED0013970-F002 | The hardware shall be sturdy enough to handle transport shocks and not require special handling when being moved.                 |

**Software**

| Requirement #     | Requirement Statement                                                                                                              |
|-------------------|------------------------------------------------------------------------------------------------------------------------------------|
| T- ED0013970-G001 | The RFPI software application shall have an EPICS interface and communication link with IOC.                                       |
| T- ED0013970-G002 | The software shall provide status indicators for communication link between RFPI hardware and RFPI application on EPICS main page. |

**Safety**

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

|                                                                                                                                                                                                                                                          |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Electrical Safety                                                                                                                                                                                                                                        |
| <ul style="list-style-type: none"> <li>FESHM Chapter 9110 Electrical Utilization Equipment Safety</li> <li>FESHM Chapter 9190 Grounding Requirements for Electrical Distribution and Utilization Equipment</li> </ul>                                    |
| Radiation Safety                                                                                                                                                                                                                                         |
| <ul style="list-style-type: none"> <li>FRCM Chapter 8 ALARA Management of Accelerator Radiation Shielding</li> <li>FRCM Chapter 10 Radiation Safety Interlock Systems</li> <li>FRCM Chapter 11 Environmental Radiation Monitoring and Control</li> </ul> |
| General Safety                                                                                                                                                                                                                                           |
| <ul style="list-style-type: none"> <li>FESHM Chapter 2000 Planning for Safe Operations</li> </ul>                                                                                                                                                        |

**Table 5.1: Safety**

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:

|                                         |
|-----------------------------------------|
| 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.

### 6.3. Design and Construction 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

## 7. VERIFICATION

### 7.1. Bench level testing

- Control systems interface
  - Verify all PVs on EPICS screens are communicating with the RFPI system appropriately. Read and write functions for PVs should be checked on bench and prior to start using RFPI chassis at PIP-II.
- Software functionality
  - Key features of RFPI application includes setting limits and clearing faults.
  - All these features need to be tested on bench
- 

## 8. QUALITY CONTROL

- RFPI System procurements shall use Fermilab standard procurement process and shall be tested prior to assembly of the RFPI system.
- Any in-kind contributions, both hardware and software, shall adhere to established protocols for same.
- Visual inspection of all circuit boards shall be completed prior to use to higher level assembly of RFPI system.
- The RFPI system shall comply with the LLRF Quality Control Plan (document #: TBD).





