PIP-II Linac RF Systems

Physics Requirement Document (PRD)

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Document Approval

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# Purpose

Physics Requirement Documents (PRDs) contain the summary parameters and configuration definitions for systems, sub-systems, and devices that impact higher-level requirements established in the PIP-II Global Requirements Document (GRD) [1]. PRDs establish a traceable link to lower-level requirements (FRSs, TRSs) that affect the PIP-II beam or machine performance. In the aggregate, the PRDs for the PIP-II Project contain the essential parameters and configuration developed through the preliminary design phase to enable completion of the PIP-II accelerator and complex design.

# Scope

The scope of this document covers the radio frequency (RF) signal chain required to provide synchronous acceleration of the ions in the PIP-II Linac. This includes the power specifications of the accelerating cavities, the loaded Q of the cavities with their input couplers, the power ratings of RF amplifiers and RF distribution, and the precision amplitude and phase regulation of the low-level RF controls. This scope also includes specifications for protection of cavities, couplers, and RF distribution components from damage from excessive RF power input. The following functional requirements are within the scope of this PRD:

* Maintain a regulated gap voltage across a cavity at a specified frequency to provide proper acceleration and focusing of the Linac beam.
* Maintain a regulated phase relationship between the gap voltages across the different cavities to provide proper acceleration and focusing of the Linac beam.
* Verify relationship between beam and RF system cavity phase advance by performing RF phase scans with beam.
* Protect cavity, couplers, and RF distribution components from excessive RF input.

# Acronyms

|  |  |
| --- | --- |
| CW | Continuous Wave |
| DAE | Department of Atomic Energy (India) |
| FRS | Functional Requirements Specification |
| GRD | Global Requirements Document |
| HB | High Beta |
| HPRF | High Power Radio Frequency |
| HWR | Half Wave Resonator |
| L2 | WBS Level 2 System |
| L3 | WBS Level 3 System |
| LB | Low Beta |
| LLRF | Low Level Radio Frequency |
| PIP-II | Proton Improvement Plan II Project |
| PIP2IT | PIP-II Injector Test |
| PRD | Physics Requirements Document |
| RF | Radio Frequency |
| RFQ | Radio Frequency Quadrupole |
| RT | Room Temperature |
| SRF | Superconducting Radio Frequency |
| SSR | Single Spoke Resonator |
| TRS | Technical Requirements Specification |

# Cavity Voltage Requirements

The overall Linac requirements define the fundamental parameters of the Linac RF system. The requirement for amplifiers is that a nominal gradient is achievable in each cavity when accelerating beam with an average beam current of 2 mA. Cavity requirements, including nominal operational voltages are documented in [2] and [3].

The following functional requirements for the RF System are derived from the overall Linac requirements:

* Maintain the beam voltage gain across the cavity to the specified precision for any beam current or pulsed beam duty factor up to the specified peak beam current.
* Maintain the specified RF frequency and relative phase between cavities to the specified precision for any beam current or pulsed beam duty factor up to the specified peak beam current.
* Inform the Linac machine protection system when RF regulation fails within the specified time window.
* Provide for arbitrary cavity voltage gain and relative phase settings for low duty beam pulses for tuning the Linac cavity parameters.

Table 4‑1 shows the configuration of cavity frequencies for the PIP-II Linac, as well as the beam current limit that the cavity will be expected to accelerate.

Table 4‑1: RT and SRF Amplifier Parameters

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Parameter** | **RFQ** | **MEBT Bunchers** | **HWR** | **SSR1** | **SSR2** | **LB650** | **HB650** |
| Frequency (MHz) | 162.5 | 162.5 | 162.5 | 325 | 325 | 650 | 650 |
| Peak Beam Current (mA) | 10 | 10 | 2 | 2 | 2 | 2 | 2 |

Figure 4‑1 shows the requested energy gain through each cavity in a typical lattice simulation for the PIP-II Linac. Figure 4‑2 shows the requested synchronous phase for each cavity in the Linac. Figure 4-3 shows the simulated transit time factor through each cavity. These values are used to calculate the RF power demand for each cavity.

Figure 4‑1: PIP-II Linac Cavity Accelerating Voltage

Figure 4‑2: PIP-II Linac Cavity Synchronous Phase

Figure 4‑3: PIP-II Cavity Transit Time Factor

## Phase and amplitude stability

The beam transport and the painting injection in the Booster require the beam energy to be stable within 0.01% rms. The tight regulation of the beam energy will be achieved through the RF-based control of fast (> a few Hz) RF field errors and beam-based control of slow drifts ($≲$1 Hz). Feedforward will be required to minimize impact of the RF field transient caused by the change in beam loading when a beam pulse passes a cavity.

The stability requirement for the field amplitude and phase is given in Table 4‑2. The requirements are same for all types of SRF cavities. The requirements were derived based on the results of particle simulations described in [4]. The simulations do not assume a time scale for the RF stability in the cavity, but this document assumes that drifts of the cavity phase that occur over 1 second of time are compensated with beam-based control.

Table 4‑2: Cavity Voltage and Phase Stability Requirements. The requirements are same for all types of PIP-II SRF cavities.

|  |  |
| --- | --- |
| **Parameter Description** | **RMS Value** |
| Cavity Voltage Amplitude Stability | 0.065% |
| Cavity Phase Stability | 0.065° |

# General RF System Conceptual Design

The block diagram of the RF System conceptual design is shown in Figure 5‑1. The diagram shows the three major subsystems within the scope of the RF system design. This includes a cavity with its associated input coupler, field probe, and tuner; an RF power amplifier with its associate transmission line and directional coupler; and a LLRF system that provides the RF signal reference that maintains the cavity field and synchronous phase. The diagram also shows two systems that are outside the scope of the RF system, timing and controls.

The conceptual design diagram also identifies interfaces that are necessary to define the technical specifications between the subsystems in this document. Some interfaces between the RF system and the timing and control system are also required to define technical specifications in this document. This design diagram does not include interlocks interfaces or general controls and data acquisition interfaces. These will not be covered in this design document.



Figure 5‑1: General RF System Conceptual Block Diagram

# SRF Cavity RF

This section describes the power demands and RF manipulations parameters required for operating the SRF section of the PIP-II Linac.

## LLRF Dynamics

The most demanding specifications on LLRF dynamics occurs when beam is injected into an SRF cavity. Power demands of the cavity increase by about a factor of four almost instantaneously. If the LLRF system responds too slowly, the error in the cavity gradient and phase will disrupt the front of the beam pulse. A simulation described in [5] shows a configuration of the RF system that can keep the gradient error below 0.065% with a 2 mA beam pulse. Table 6‑1 shows the concluding results of the simulation in terms of delay budget, proportional gain, and allowable errors in RF feedforward.

Table 6‑1: LLRF Dynamics Specifications

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Delay Budget | 5000 us max |
| Amplifier Delay | 100 ns max |
| RF Power Distribution Delay | 500 ns max |
| RF Fanback and Drive Delay | 600 ns max |
| LLRF System Delay | 3800 ns max |
| LLRF System Proportional Gain | 40 dB min |
| Feedforward Error Vector Magnitude | 10% max |
| Error in Feedforward Program Timing | 500 ns max |
| Overshoot Budget for Power Amplifier | 15% |

The delay budget has been broken down into budgets for different components in the RF system. These values are a placeholder for the delay requirements flow down to the different components. The delay budget can be negotiated between the different systems as the design progresses, keeping the total delay within the overall budget.

# CW-Compatible Regime and Pulsed Operations

The GRD requires that all systems and components are constructed and installed with a capability to support CW-RF and pulsed-beam operations at the project completion. These systems, within the scope of this PRD, are identified as being required to support CW-compatible operations as installed by the PIP-II Project:

* Warm front end (RFQ and buncher cavities): As currently fabricated and installed at the PIP-II Injector Test (PIP2IT), all warm front-end components are capable of CW-beam operation. This capability will be retained when these components are relocated to the PIP-II Linac enclosure.
* Superconducting cavities and cryomodules: All cavities and cryomodules, including RF couplers, will be constructed with a capability for CW-beam operations. In particular, the specification for cavity Q0 will be established on the basis of CW operations.
* RF Sources: All RF sources and RF distribution infrastructure will be constructed with a capability for CW-beam operations.
* Low level RF (LLRF): The LLRF system will be capable of supporting CW-RF within the superconducting cavities, during pulsed-beam operations.

Development of pulsed-RF capability in the SRF section of the Linac is motivated by two factors: a) the interest to support the DAE partners’ plans to construct a pulsed-RF superconducting Linac (ISNS), and b) the desire to operate PIP-II in a cost-efficient operating mode. Pulsed capability of the RF amplifiers and LLRF system are an intrinsic part of the pulsed-beam operations specifications. Specifications for resonance control of SRF cavities are not currently consistent with pulsed-RF operations, because the design parameters for CW/pulsed-RF compatible SRF cavities and resonance control systems have not demonstrated with these cavities.

# RF Power Requirements

## SRF Cavity Power Requirements

Cavity RF power requirements depend on the cavity and beam parameters. The beam voltage and synchronous phase requirements are collected in Section 4 of this document, and a maximum average beam current of 2.0 mA is assumed for all power demand calculations. The power must also compensate for cavity detuning, which is assumed not to exceed 20 Hz for all types of cavities.

Table 8‑1 shows the specific SRF cavity parameters used to determine the power required at the cavity input coupler. The optimal coupling of the cavity input couplers is calculated from the cavity and beam parameters. The calculation assumes that the coupling factor will be fixed for each style of cavity, and the optimal coupling will be derived from the cavity of each type with the highest power demand. Also, the available power requirement allows for up to a 25% variation from design specification in the coupling, to allow for mechanical tolerances in manufacture.

Table 8‑1. SRF Cavity RF Requirements.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Parameter** | **HWR** | **SSR1** | **SSR2** | **LB650** | **HB650** |
| Frequency (MHz) | 162.5 | 325 | 325 | 650 | 650 |
| Q0 | 8.5e9 | 8.2e9 | 8.2e9 | 23e9 | 32e9 |
| QL | 2.3e6 | 3.0e6 | 5.1e6 | 10.4e6 | 9.9e6 |
| R/Q (Ω) | 272 | 242 | 297 | 340 | 610 |
| Peak RF Power at Coupler without margins (kW) | 4.5 | 4.4 | 12.5 | 29.2 | 44.3 |

## SRF Amplifier Parameters

The amplifier power also must account for power losses during RF transfer from the RF amplifier in the gallery to the SRF cavities. This loss is assumed to be 15% for HWR, SSR, and SSR2 cavities and 10% for LB650 and HB650 cavities.

Table 8‑2. SRF Amplifier Parameters. specifies the required amplifier power for each cavity type based on the peak power at the input coupler, the transmission efficiency, and the operational overshoot budget. This overhead was derived in Section 6 of this document and listed in Table 6‑1. The amplifier power is assumed to correspond to the 1 dB compression point of the amplifier power response. If the amplifier becomes too non-linear to make the requested power demand, the LLRF system will not be able regulate the cavity field adequately.

Table 8‑2. SRF Amplifier Parameters.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Parameter** | **HWR** | **SSR1** | **SSR2** | **LB650** | **HB650** |
| Frequency (MHz) | 162.5 | 325 | 325 | 650 | 650 |
| RF Transfer Line Power Efficiency  | 85% | 85% | 85% | 90% | 90% |
| Overshoot Budget | 15% | 15% | 15% | 15% | 15% |
| Amplifier power (kW) | 0.41\* / 6.2 | 6.1 | 17.3 | 38.2 | 57.9 |

\*- Power of the first HWR amplifier

## Equipment Protection

The SRF cavity and input coupler need to be protected from damage when a quench or electrical fault (multipacting or spark) occurs in the vacuum section. It assumes that there is no way to remove the stored energy in the cavity once a quench or fault occurs. All components connected to the cavity, including the cavity itself, must be able to withstand the full stored energy of the cavity in the event of a fault condition. The RF protection system is specified to ensure that the components are not exposed to more than 10% of extra energy from the RF power amplifiers than components would be exposed to from the cavity energy. Table 8‑3 summarizes the cavity stored energy parameters that can be created in a fault condition. The response time of the interlocks is derived from the 10% limit and the maximum amplifier output power.

Table 8‑3: SRF Equipment Protection Parameters

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Parameter** | **HWR** | **SSR1** | **SSR2** | **LB650** | **HB650** |
| Peak Return Power from Cavity Decay (kW) | 8.9 | 6.6 | 23 | 55 | 89 |
| Cavity Decay Time at Peak Energy (ms) | 2.99 | 1.93 | 2.89 | 2.95 | 3.07 |
| Max Energy to Fault Condition (J) | 16.6 | 9.4 | 45 | 110 | 173 |
| Interlocks Response Time (us) | 248 | 140 | 236 | 262 | 272 |

## Resonant Control

This document does not cover the mechanism to keep cavity microphonics below the 20 Hz detuning limit. This is an assumed specification from the vibration PRD. However, the optimal detuning can be significantly off resonance for matching to the beam loading. The resonant controls should keep the resonant frequency within 6 Hz of optimal detuning for beam loading. This allows for peak microphonics detuning of 14 Hz while still maintaining the 20 Hz, overall detuning limit.

## Room Temperature Cavity Power Requirements

Table 8‑4 lists the room temperature cavity RF requirements.

Table 8‑4. Room Temperature Cavity RF Requirements.

|  |  |  |
| --- | --- | --- |
| **Parameter** | **RFQ** | **WFE Bunching** |
| Frequency (MHz) | 162.5 | 162.5 |
| Power transmitted to beam (kW, nominal voltage, 5 mA) | 21 | 0.35 |
| Cavity Q0 | 13000 | 10020 |
| Cavity Loaded Q | 6100 | 5090 |
| Peak RF Power at Couplers (x2) | 50 | 0.9 |

# RF Phase Reference Stability Requirements

Accuracy of the synchronous phase in the cavity relative to beam is most sensitive to the accuracy of the RF phase reference used to identify errors in the cavity gradient phase. This analysis of the required stability and accuracy of the reference assumes that the detected cavity gradient goes through an analog down converting process to an intermediate frequency that is digitally sampled. The cavity gradient is not directly sampled by a digital system. This analysis also assumes that the reference errors at the down converter dominate the synchronous phase error and is approximately one-to-one.

This analysis focuses on two forms of error in the reference line, random errors due to jitter in the reference phase, and slow, relatively fixed errors, generally caused by thermal effects in the reference distribution. The effect of the errors has the greatest effect on the 650 MHz reference system where phase errors are most sensitive to timing errors. The total rms phase error for the specified phase jitter is about a quarter of the phase stability budget specified in Table 4‑2. The slow drift specification allows for thermal effects on the reference line to move the beam synchronous phase beyond the phase stability budget in 4 seconds. These specifications are summarized in Table 9‑1. The beam energy correction system for beam injection will be required to respond in this time to maintain proper energy matching.

Table 9‑1. RF Phase Reference Line Parameters.

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Frequency compatibility | 162.5, 325, 650 MHz |
| Phase jitter requirement (@ 8 kHz bandwidth) | 0.073 ps rms max |
| Slow drift requirements | 0.073 ps / sec max |

# Reference Documents

|  |  |  |
| --- | --- | --- |
| **#** | **Reference** | **Document #** |
| 1 | PIP-II Global Requirements Document (GRD) | ED0001222 |
| 2 | PIP-II Superconducting Linac Parameters (PRD) | ED0010221 |
| 3 | PIP-II Parameters PRD | ED0010216 |
| 4 | Analysis of Linac Energy Jitter | PIP-II DocDB #2976 |
| 5 | PIP-II RF Control Simulation for SRF Cavities with Pulsed Beam Loading | EN03775 |