PIP-II Beam Instrumentation Functional Requirements Specification

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Document Approval

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Revision History

Revision	Date of Release	Description of Change
--	8/18/2021	Initial Draft
A	11/11/2021	(cadornaa) Edited Assumptions, F-121.3.09-A008, F-121.3.09-A009 Added F-121.3.09-A0014, F-121.3.09-A0013
B	3/31/2023	(cadornaa) Added PIPdocDB for QC plan; Updated to have consistent naming between FRS, TRS, ISD documents; Split F-121.3.09-A010 to cover LW and WS separately. Consolidated F-121.3.09-B003/-B004/-B005; Renumbered FRS statements; Added new F-121.3.09-D003
C	July 2023	(cadornaa) Updated for BCM/BLM/BPM FDR
D	Feb 2024	(cadornaa) Updated Approval Chain; Added references to BI Phase Reference Line

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1. PURPOSE

A Functional Requirements Specification (FRS) document describes the project needs and/or requested behavior of a system or component. The FRS 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 FRS addresses the functional requirements of the 4 core Beam Instrumentation (BI) systems, from the PIP-II warm front-end (WFE), through the superconducting Linac (SCL), and through beam transport line (BTL) into the Booster ring. This suite of systems will characterize and monitor the beam parameters and the performance in all PIP-II sub-accelerators from commissioning to normal operations. [1]:

1. Beam Position Monitor (BPM) Systems [11]
2. Beam Loss Monitor (BLM) Systems [12]
3. Beam Current Monitor (BCM) Systems [13]
4. Beam Profile Monitor (BProM) Systems [14][15]

Figure 2-1 : Summary of Measurements Provided by BI Systems
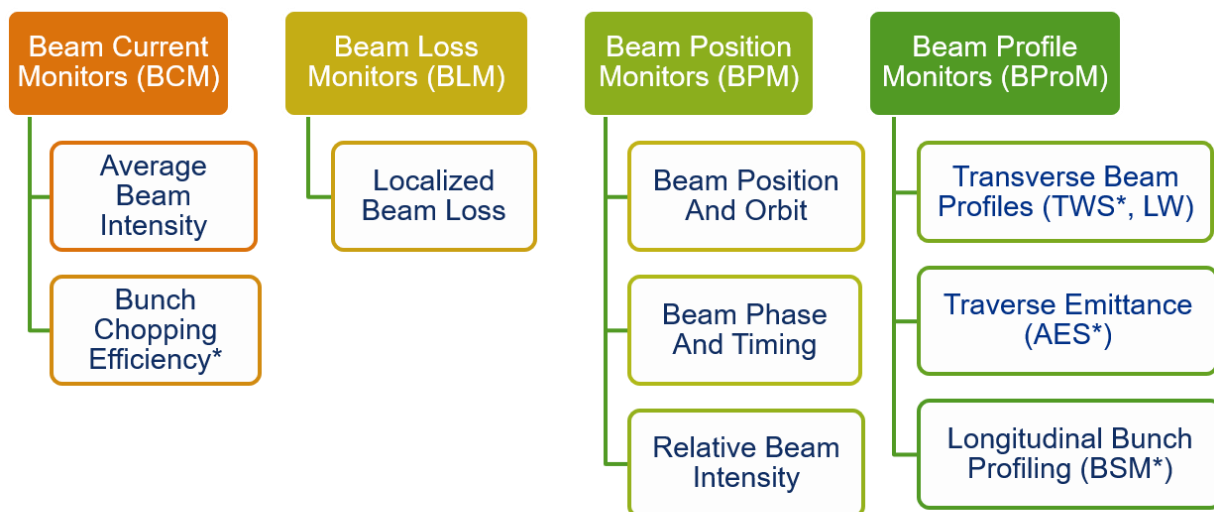
For Beam Diagnostic Modes Only

3. KEY ASSUMPTIONS

Key cost, schedule, technical and programmatic assumptions are provided in PIP-II Project Assumptions [2].

4. ACRONYMS

ACCT	AC Current Transformer
AES	Allison Emittance Scanner
BCM	Beam Current Monitor
BI	Beam Instrumentation
BLM	Beam Loss Monitor
BPM	Beam Position Monitor
BProM	Beam Profile Monitor
BSM	Bunch Shape Monitor
BTL	Booster Transfer Line
DCCT	DC Current Monitor
FEM	Fermilab Engineering Manual
FESHM	Fermilab ES&H Manual
FQAM	Fermilab Quality Assurance Manual
FRCM	Fermilab Radiological Control Manual
FRS	Functional Requirements Specification
GRD	Global Requirements Document
L2	WBS Level 2
L3	WBS Level 3
LEBT	Low Energy Beam Transport
LLRF	Low Level Radio Frequency
MEBT	Medium Energy Beam Transport
MPS	Machine Protection System
PIP-II	Proton Improvement Plan II Project
PRD	Physics Requirements Document
QA	Quality Assurance
QC	Quality Control
RWCM	Resistive Wall Current Monitor
SCL	Superconducting Linac
TC	Teamcenter
TRS	Technical Requirements Specification
TWS	Transverse Wire Scanner
WBS	Work Breakdown Structure
WFE	Warm Front End

5. FUNCTIONAL REQUIREMENTS

For commissioning and normal operations [3], BI will provide a suite of beam instrumentation systems, whose primary functions are to observe beam position and phase, beam losses, beam profiles, and beam current and intensity as well as to characterize beam emittance, transverse beam halo, bunch-by-bunch chopping efficiency, and advanced beam emittance measurements.

Table 5-1 through Table 5-5 provide the functional requirements for each BI system. These functional requirements are driven by higher-level requirements set by the PIP-II GRD[4], PIP-II Parameters PRD[5], PIP-II BI PRD[6], PIP-II Vacuum PRD[7], PIP-II Misalignment Tolerances PRD[8], and PIP-II MPS PRD[9].

5.1. Functional Requirements Tables

Table 5-1. BI Alignment Requirements

Requirement	Requirement Statement
F-121.3.09-A001	Alignment services shall provide as-found alignment measurements to locate the BPM position and orientation in the MEBT, SCL, BTL, and diagnostic cart.
F-121.3.09-A002	Invasive BProM system shall have fiducials to allow for proper alignment to the mechanical center of the beam pipe by alignment services.
F-121.3.09-A003	Non-Invasive BProM system and laser-based optics shall have fiducials to allow for proper alignment to the mechanical center of the beam pipe by alignment services.

Table 5-2. BCM Functional Requirements

Requirement	Requirement Statement
F-121.3.09-BCM01	BCM systems shall be capable of measurements of short commissioning beam pulses as well as nominal length operational beam pulses, for pulse repetition rates up to 20 Hz.
F-121.3.09-BCM02	Noninvasive BCM systems, with DCCT pickups, shall measure the average beam current out from the ion source and into the SCL.
F-121.3.09-BCM03	Noninvasive BCM systems, with ACCT pickups, shall measure the average beam current for each beam pulse in the WFE, SCL, BTL, and diagnostic cart.
F-121.3.09-BCM04	Noninvasive BCM systems with RWCM pickups shall measure the bunch-by-bunch chopping pattern and chopping efficiency, when requested.
F-121.3.09-BCM05	Invasive BCM systems shall measure the instantaneous beam current for each beam pulse in the WFE, relative to an adjustable trigger.
F-121.3.09-BCM06	BCM systems shall provide signals for differential beam current measurements in the MPS for each beam pulse.

Table 5-3. BPM Functional Requirements

Requirement	Requirement Statement
F-121.3.09-BPM01	BPM systems shall be capable of measurements of short commissioning beam pulses as well as nominal length operational beam pulses, for pulses repetition rates up to 20 Hz.
F-121.3.09-BPM02	BPM systems shall measure the transverse horizontal and vertical beam positions at each focusing element for the WFE, SCL, BTL, and diagnostic cart for each beam pulse.
F-121.3.09-BPM03	BPM systems shall measure the relative average beam intensity at each focusing element for the WFE, SCL, BTL, and diagnostic cart for each beam pulse.
F-121.3.09-BPM04	BPM systems, in the MEBT chopper section, shall provide bunch by bunch transverse position and intensity measurements.
F-121.3.09-BPM05	BPM systems, in the MEBT and SCL, shall measure the beam phase, calibrated with respect to a 162.5MHz reference line, at each focusing element for beam pulse.
F-121.3.09-BPM06	BPM systems shall be capable of providing the beam energy measurements between 2 consecutive pre-determined BPMs in the MEBT, provided no RF cavities are between them.
F-121.3.09-BPM07	BPM systems, in the diagnostic cart, shall be capable of providing time of flight measurements.
F-121.3.09-BPM08	BPM system shall receive the LLRF 162.5 MHz signal and distribute it within the MEBT and SCL for Beam Instrumentation systems.
F-121.3.09-BPM09	The room temperature BPM pickups in the MEBT, SCL, BTL, and diagnostic cart shall have the capability to be pinned and mounted directly to the steel of the adjacent focusing quadrupole magnets.
F-121.3.09-BPM10	Large aperture BTL BPM systems shall provide beam trajectory information at beginning of absorber line.

Moreover, F-121.3.09-BPM05 and F-121.3.09-BPM08 apply to the BI Phase Reference Line.

Detailed specifications are further provided in the BI Phase Reference Line FRS [10].

Table 5-4. BLM Functional Requirements

Requirement	Requirement Statement
F-121.3.09-BLM01	BLM systems shall be capable of measurements of short commissioning beam pulses as well as nominal length operational beam pulses, for pulse repetition rates up to 20 Hz.
F-121.3.09-BLM02	BLM systems shall measure relative beam loss for each beam pulse in the WFE, SCL BTL, and diagnostic cart.
F-121.3.09-BLM03	BLM pickup selection and design shall be based on localized particle production types and rates for estimated beam losses at the beam energy for a given location.
F-121.3.09-BLM04	Locations of BLM pickups shall be determined by maps of radiation dose induced by beam losses, provided by simulations using the MARS Monte-Carlo code.
F-121.3.09-BLM05	BLM systems shall provide signals to the MPS that ensure that beam is interrupted if conditions where localized beam loss has exceeded predetermined safety thresholds.

Table 5-5. BProM Functional Requirements

Requirement	Requirement Statement
F-121.3.09-BPR01	TWS BProM systems shall provide average transverse beam profiles when requested.
F-121.3.09-BPR02	AES BProM systems shall measure the beam transverse emittance when requested.
F-121.3.09-BPR03	BSM BProM systems shall provide average longitudinal bunch profiles when requested.
F-121.3.09-BPR04	LW BProM systems shall provide average transverse beam profiles when requested.
F-121.3.09-BPR05	Invasive BProM systems shall provide signals to the MPS to ensure that the beam is interrupted if conditions, where a beam-induced damage may occur, are detected.
F-121.3.09-BPR06	Noninvasive BProM system shall utilize a low-vacuum optical transport line, that is optically straight for its entire length.

6. CONSTRUCTION STANDARDS

Development of BI system components and architectures shall also abide by guidelines, requirements, and best practices, outlined in FEM [18].

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**
- **CGA S-1.3 Pressure Relief Standards**
- **NFPA 70 – National Electrical Code**
- **IEC Standards for Electrical Components**
- **UL61010 - Laboratory equipment**
- **UL60950 - Computing/Telecommunication Equipment**
- **ASHRAE - Datacenter Standards**
- **IPC-JSTD-001 – Soldering**
- **IPC2221 – Printed Circuit Board spacing and design**
- **IPC-A-600 -- Printed Circuit Board acceptance and testing**
- **IPC-A-610 -- Electronics assembly**

Additional design and construction standards, which are not listed in the general list above or within Section 5, shall be elaborated in the TRS for the relevant BI system [11] [12] [13] [14] [15] [16] [17]. 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.

7. SAFETY REQUIREMENTS

BI systems shall abide by FESHM [19] and FRCM [20] requirements, including those in the table below. Also, in cases where International Codes and Standards are used, the BI system shall follow FESHM Chapter 2110: *Ensuring Equivalent Safety Performance Using International Codes and Standards* [19]. :

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 • FESHM Chapter 10000 Material Handling and Transportation

Additional safety requirements, which are not listed in the general list above, shall be elaborated in the relevant BI system [11] [12] [13] [14] [15] [16] [17]. 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.

8. QUALITY ASSURANCE PROVISIONS

At a minimum, BI systems shall adhere to FQAM [21], PIP-II Procurement Plan [22], PIP-II 121.03 Accelerator Systems QA Plan [23], and PIP-II Beam Instrumentation QC Plan [24].

9. REFERENCE

	Reference	Document
1	PIP-II Commissioning and Start-Up Plan	PIP-II docDB 5420
2	PIP-II Project Assumptions	PIP-II docDB 144
3	PIP-II Accelerator Commissioning and Operations Beam and Machine Modes	PIP-II docDB 6998
4	PIP-II Global Requirements Document (GRD)	ED0001222
5	PIP-II Parameters Physics Requirements Document (PRD)	ED0010216
6	PIP-II Beam Instrumentation PRD	ED0010230
7	PIP-II Vacuum PRD	ED0010288
8	PIP-II Misalignment Tolerance PRD	ED0010231
9	PIP-II Machine Protection System PRD	ED0010232
10	PIP-II BI Phase Reference Line Functional Requirement Specification (FRS)	ED0030105
11	PIP-II BPM Technical Requirement Specification (TRS)	ED0013710
12	PIP-II BLM TRS	ED0013711
13	PIP-II BCM TRS	ED0013712
14	PIP-II Invasive BProM TRS	ED0013713
15	PIP-II Noninvasive BProM TRS	ED0013714
16	PIP-II DAQ Electronics TRS	ED0013715
17	PIP-II BI Phase Reference Line TRS	ED0030047
18	Fermilab Engineering Manual (FEM)	-
19	Fermilab Environmental Safety and Health Manual (FESHM)	-
20	Fermilab Radiological Control Manual (FRCM)	-
21	Fermilab Quality Assurance Manual (FQAM)	-
22	PIP-II Procurement Plan	PIP-II docDB 522
23	PIP-II 121.03 Accelerator Systems Quality Assurance (QA) Plan	PIP-II docDB 4805
24	PIP-II Beam Instrumentation Quality Control (QC) Plan	PIP-II docDB 5520