Beam Instrumentation

Document number:

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 document describes requirements for the diagnostics and instrumentation for the PIP-II SCL and the Beam Transfer Line from the PIP-II SCL to Booster.

# Acronyms

|  |  |
| --- | --- |
| ACCT | AC Current Transformer |
| BLM | Beam Loss Monitor |
| BPM | Beam Position Monitor |
| BTL | Beam Transfer Line |
| DAQ | Data Acquisition |
| DCCT | DC Current Transformer |
| EID | Electrically Isolated Diaphragm |
| FRS | Functional Requirements Specification |
| GRD | Global Requirements Document |
| L2 | WBS Level 2 System |
| L2M | WBS Level 2 Manager |
| L3 | WBS Level 3 System |
| L3M | WBS Level 3 Manager |
| LEBT | Low Energy Beam Transport |
| PIP-II | Proton Improvement Plan II Project |
| PIP2IT | PIP-II Injector Test |
| MEBT | Medium Energy Beam Transport |
| PMT | Photomultiplier Tube |
| PRD | Physics Requirements Document |
| RT | Room Temperature |
| SCL | Superconducting Linac |
| RWCM | Resistive Wall Current Monitor |
| TRS | Technical Requirements Specification |
| WFE | Warm Front End |

# Definitions and Assumptions

Resolution, or precision, is associated with the standard deviation of many measurements. Examples are:

* Quantization error of DAQ
* Errors associated with reproducibility of positioning moving mechanical components
* Measurement errors caused by random noise

Accuracy refers to a systematic offset from the ideal condition or set point, often when averaged over many measurements. Examples are:

* Scale and calibration errors
* Systematic offsets and positioning errors are not considered

# Overview

PIP-II diagnostics and instrumentation are included in the following systems, see Table 5‑1:

Table ‑. PIP-II Diagnostics by System

|  |  |  |  |
| --- | --- | --- | --- |
|  | **WFE** | **SCL** | **BTL** |
| **Beam transverse position and energy in dispersion area.**  **Beam phase relatively to RF.** | | | |
| Warm BPM | X | X | X |
| Cold BPM |  | X |  |
| **Beam transverse profiles** | | | |
| Laser profiler | X | X |  |
| Beam scrapers | X |  |  |
| Wire profiler | X |  | X |
| **Beam transverse emittance** | | | |
| Allison-style scanner | X |  |  |
| Laser scanner |  |  | X |
| **Beam longitudinal profiles** | | | |
| Laser profiler | X |  |  |
| Feschenko wire profiler |  |  | X |
| **Beam current and intensity** | | | |
| ACCT | X | X | X |
| DCCT | X | X |  |
| RWCM | X | X |  |
| Scrapers | X |  |  |
| Electrical isolated pickups | X |  |  |
| **Beam loss** | | | |
| PMT loss monitor | X | X |  |
| Neutron loss monitor | X | X |  |
| Ionization loss monitor |  | X | X |

The tables under Section 8 provide requirements for a corresponding system without specifying quantities. The quantities of systems and their exact location on the beam lines are reflected in the PIP-II Parameters PRD [2] as well as in the Lattice file [3].

# General Requirements

## Vacuum requirements

Beam line instrumentation devices comply with the vacuum requirements described in the PIP-II Vacuum PRD [4]. Instrumentation devices are manufactured and processed in a manner compatible with the operational pressure and other requirements described in the Vacuum PRD (e.g. particle-free to be SRF compatible). Technical requirement specifications (TRS) can specify additional processing requirements such as heat treatment (baking).

## Space requirements

Beam instrumentation such as laser wires, beam intensity diagnostics, and BPMs in the SCL are placed between cryomodules. The drift space between cryomodules available for instrumentation is very limited due to beam dynamics limitations and space occupied by other systems such as focusing magnets and vacuum components. Due to these limitations and based on estimates of geometrical dimensions of instrumentation, the distance allocated for the instrumentation between cryomodules (any) is 250 mm. The PIP-II Parameters PRD [2] and the Lattice file [3] document the distance between specific cryomodules and components.

# Beam Parameters

The PIP-II Parameters PRD [2] documents the PIP-II beam parameters for nominal beam operations and the range for these parameters under commissioning. This beam information is used to define the beam instrumentation performance under these conditions.

# Requirements

## Beam Position Monitors

### General functional requirements

Beam position/orbit monitoring is the most fundamental measurement and powerful diagnostics tool in an accelerator. PIP-II requires a significant number of warm and cold BPM for the SCL and 800 MeV transfer beam line. Both the warm and cold BPMs must be capable of measuring all three coordinates: horizontal and vertical position and beam phase relative to the RF. The beam line design includes a single four-button BPM located near each beam focusing element (solenoid, quad, doublet, triplet). The geometry of all BPMs will be similar with their aperture scaled in size as required.

General functional requirements for BPMs

* Measure coordinates of the beam transverse position/orbit
* Measure the relative beam phase
* Measure the relative beam intensity

In addition, BPMs in the MEBT chopper section will be used to measure individual orbits of the chopped and un-chopped beam going through simultaneously. This requires an additional chopper BPM system with a bandwidth able to measure individual bunch positions. This wideband BPM system will not measure beam phase or 1st harmonic intensity. This wideband BPM system will operate in parallel with the standard BPM system in the chopper section of the MEBT.

### MEBT BPMs

Location: MEBT, next to MEBT quadrupoles.

Table ‑. MEBT BPM Parameters, non-chopper section

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal Beam | Commissioning Beam |
| Position resolution | 10 m | 250 m |
| Position accuracy (rms) | 0.1 mm | 0.5 mm |
| 1st Harmonic Intensity resolution | 1 % | 10 % |
| Phase resolution | 0.3° @ 162.5 MHz | 5o @ 162.5 MHz |
| Beam aperture | 30 mm | |
| Operational temperature | +15 to +30 ºC | |

Location: MEBT, next to MEBT quadrupoles, in chopper section, high-bandwidth system.

Table ‑. MEBT BPM Parameters, chopper section, high-bandwidth bunch-by-bunch system

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal Beam | Commissioning Beam |
| Position resolution | 100 m | 2 mm |

### HWR, SSR1 and SSR2 BPMs

Location: Internal to HWR, SSR1 and SSR2 cryomodules, next to each focusing solenoids.

Table ‑. HWR, SSR1 and SSR2 Cryomodule BPM Parameters

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal Beam | Commissioning Beam |
| Position resolution | 10 m | 250 m |
| Position accuracy (rms) | 0.1 mm | 0.5 mm |
| 1st Harmonic Intensity resolution | 1% | 10% |
| Phase resolution | 0.3° @ 162.5 MHz | 5° @ 162.5 MHz |
| Beam aperture (HWR / SSR1 / SSR2) | 32 mm / 30 mm / 40 mm | |
| Operational temperature | 2 to 45 K | |

### BPMs in RT sections of LB650, HB650 and in the Beam Transfer Line (BTL)

Location: RT sections of SCL, BTL, next to RT quadrupoles

Table ‑. RT Sections of SCL and BTL BPM Parameters

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal beam | Commissioning Beam |
| Position resolution | 10 m | 250 m |
| Position accuracy (rms) | 0.1 mm | 0.5 mm |
| 1st Harmonic Intensity resolution | 1% | 10% |
| Phase resolution | 0.3° @ 162.5 MHz | 5° @ 162.5 MHz |
| Beam aperture | 50 mm | | |
| Operational temperature | +15 to +30 ºC | | |

### Large aperture BPMs

Location: In front of the Lambertson septum magnet in BTL

Table ‑. Large Aperture BPM Parameters

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal Beam | Commissioning Beam |
| Position resolution | 50 m | 0.5 mm |
| Position accuracy (rms) | 0.2 mm | 1 mm |
| 1st Harmonic intensity resolution | 2% @ 162.5 MHz | 10% @ 162.5 MHz |
| Phase resolution | 1° @ 162.5 MHz | 10° @ 162.5 MHz |
| Beam aperture | 150 mm\* | |
| Operational temperature | +15 to +30 ºC | |

\* - preliminary, to be finalized during final design.

## Beam Profile and Beam Emittance

Two types of transverse wire profiling methods for PIP-II are being considered for most locations. The first method would use photo-disassociation of H− by laser radiation, and the second method would be a traditional wire scanner. Because of the minimal interaction with the beam, the laser-based profile monitor will be the only profiling method allowed near the superconducting cryomodules. Because of their proven technology, wire scanners will be the primary choice in the 800 MeV transfer line. In addition to these two primary choices for transverse profiles, transverse scrapers in the LEBT and MEBT will be utilized to produce beam profile measurements.

Transverse emittance measurements are a highly useful and versatile tool for the tuning and operation of an accelerator. There are various techniques that can be used to determine the transverse emittance. PIP-II will employ two types of emittance measurements for transverse phase-space: (1) Allison-type emittance scanners and (2) laser-based emittance scanners. The Allison-type emittance scanner will be used in the LEBT and MEBT of the WFE. The laser-based emittance scanner will be utilized in the beginning of the BTL.

PIP-II will utilize two methods for longitudinal bunch shape profiles: (1) a picosecond laserwire in the WFE MEBT to make longitudinal measurements and (2) a Feschenko-style [7] wire-based bunch shape monitor at the end of the SCL.

### Laser Wire

Location: WFE/MEBT, SCL, end of SCL, BTL

General functional requirements:

* Measure transverse distribution, including its shape and coordinates, process the data

Table ‑. Laser Wire Parameters

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal Beam | Commissioning Beam |
| Beam energy | 2.1, 800 MeV | 2.1, 800 to 833 MeV |
| Beam pulse length | 10 μs | 5 to 10 s |
| Bunch Intensity | 30 pC | 1.2 to 60 pC |
| Bunch Intensity (particles) | 1.5e8 | 6e7 to 3e8 |
| Beam transverse size (rms) | 2 mm | 1 to 4 mm |
| Transverse resolution | 100 m | 250 m |
| Transverse accuracy (rms) | 0.25 mm | 1 mm |
| Size of measurable region | ±15 mm | ±15 mm |
| Desirable typical scan time | <3 min | <5 min |
| Min Beam aperture (WFE / SCL / BTL) | 30 mm / 50 mm / 50 mm | |
| Operational temperature | +15 to +30 ºC | |

### Wire Profile Monitor

Location: WFE, BTL

General functional requirements:

* Measure transverse distribution, including its shape and coordinates, process the data.

Table ‑. Wire Profile Monitor Parameters

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal Beam | Commissioning Beam |
| Beam energy | 2.1, 800 MeV | 2.1, 800 to 833 MeV |
| Beam pulse length | 10 μs | 5 to 10 s |
| Bunch Intensity | 30 pC | 1.2 to 60 pC |
| Bunch Intensity (particles) | 1.5e8 | 6e7 to 3e8 |
| Beam transverse size (rms) | 2 mm | 1 to 4 mm |
| Transverse resolution | 100 m | 250 m |
| Transverse accuracy | 0.5 mm | 1.0 mm |
| Size of measurable region | ±20 mm | | |
| Desirable typical scan time | <3 min | | |
| Min Beam aperture (WFE / SCL / BTL) | 30 mm / 50 mm / 50 mm | | |
| Operational temperature | +15 to +30 ºC | | |

### Allison Emittance Scanner

Location: LEBT and MEBT

General functional requirements:

* Measure and output the transverse phase space distribution.

Table ‑. Allison Emittance Scanner Parameters

|  |  |  |
| --- | --- | --- |
| Parameter | LEBT | MEBT |
| Beam energy | 30 KeV | 2.1 MeV |
| Beam pulse length | 10 μs to CW | 10 – 60 s |
| Beam current range | 0.2 mA to 10 mA | 0.2 mA to 10 mA |
| Average Maximum Beam Power | 300 W | 60 W |
| Positioning reproducibility | 100 μm | 100 μm |
| Positioning accuracy | 1 mm | 1 mm |
| Positioning step | 25 μm | 25 μm |
| Angular resolution | 0.5 mrad | 0.2 mrad |
| Angular accuracy | 10 mrad | 10 mrad |
| Intensity resolution | 1 % | 1 % |
| Intensity accuracy | 5 % | 5 % |
| Scanning stroke | ±30 mm | ±15 mm |
| Angular sweep | ±80 mrad | ±10 mrad |
| Desirable typical scan time | <3 min | <3 min |
| Operational temperature | +15 to +30 ºC | |

### Longitudinal Beam Profiles

Location: WFE, SCL, end of SCL

General functional requirements:

* Measure average longitudinal bunch distribution, including its shape and coordinates, process the data.

Table ‑. Laser Wire Longitudinal Profiles

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal Beam | Commissioning Beam |
| Longitudinal resolution | 20 psec | 40 psec |
| Size of measurable region  (degrees of phase @ 162.5 MHz) | 360º | 360º |
| Desirable typical scan time | <5 min | <8 min |
| Min Beam aperture (WFE / SCL / BTL) | 30 mm / 50 mm / 50 mm | |
| Operational temperature | +15 to +30 ºC | |

Laser Wire Profile Monitors will not be able to resolve the nominal longitudinal bunch profile in the SCL downstream of the Warm Front End. However, Laser Wire Monitors in the SCL still can be used to measure the longitudinal profile of bunches that are allowed to drift and elongate without acceleration and longitudinal focusing. This technique will be used to measure the longitudinal emittance of the beam.

Table ‑. Feschenko-style Longitudinal Profiles

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal Beam | Commissioning Beam |
| Longitudinal resolution | 4 psec | 8 psec |
| Size of measurable region  (degrees of phase @ 162.5 MHz) | 90º | 90º |
| Desirable typical scan time | <5 min | <8 min |
| Min Beam aperture (WFE / End of SCL) | 30 mm / 50 mm | | |
| Operational temperature | +15 to +30 ºC | | |

## Beam and Bunch Intensity Monitors

A combination of invasive and non-invasive beam current instruments will be used to adequately cover the proposed range of beam timing structures. The invasive pickups include electrically isolated pickups, which consist of EIDs, beam absorbers/dumps, kicker protection electrodes, insertable scrapers, and an electrically isolated beam pipe aperture restriction. Non- invasive pickups include the DCCT, ACCT, and RWCM. Aside from the RWCM, these pickups will provide instantaneous or average beam current measurements. RWCM will be employed to measure the bunch-by-bunch chopping pattern and the chopping efficiency.

In addition, an accurate measure of beam current loss computed from the difference of beam currents at different locations along the beamline is required for the MPS. DCCT and ACCT provide primary inputs to the MPS system. Also, several dedicated ring pickups, which are like single button BPMs, will be employed in the PIP-II WFE to give an independent measure of the relative beam current for the MPS. Exact requirements on the Ring Pickup is covered within the scope of the MPS.

Calibration of these beam current pickups is critical to maintain accurate measurements. The PIP-II beam current monitoring system will employ a semi-automated calibration system allowing for nominal calibration times of minutes or less.

### DCCT

Location: WFE, end of SCL

General functional requirements:

* Measure DC current component to control total beam current out of ion source and into SRF cryomodules

Table ‑. DCCT Parameters

|  |  |
| --- | --- |
| Parameter | Value |
| Intensity resolution (rms) | <1 mA / sqrt(Hz) |
| Intensity accuracy | ±0.1% |
| Time response | DC to 10 kHz |
| Min Beam aperture (WFE / SCL / BTL) | 30 mm / 50 mm / 50 mm |
| Approx. slot length | 120 mm |
| Operational temperature | +15 to +30 ºC |
| Temperature coefficient | <0.5 µA/ºC typical |

### ACCT

Location: WFE, SCL, BTL

General functional requirements:

* Measure current of pulsed beam, intensity measurements for SCL tuning, operations, and MPS

Table ‑. ACCT Parameters

|  |  |
| --- | --- |
| Parameter | Value |
| Intensity resolution (rms) | 1.5 A |
| Intensity accuracy | ±1% |
| Bandwidth | 3 Hz to 1 MHz |
| Min Beam aperture (WFE / SCL / BTL) | 30 mm / 50 mm / 50 mm |
| Approx. slot length | 40 mm |
| Operational temperature | +15 to +30 ºC |

### Resistive Wall Current Monitors

Location: WFE/MEBT, SCL

General functional requirements:

* Measurement of bunch-by-bunch chopper efficiency

Table ‑. Resistive Wall Current Parameters

|  |  |
| --- | --- |
| Parameter | Value |
| Bandwidth (MHz) | 0.01 to 4000 MHz |
| Min Beam aperture (WFE / SCL / BTL) | 30 mm / 50 mm / 50 mm |
| Approximate slot length (mm) | 50 mm |
| Operational temperature | +15 to +30 ºC |

### Adjustable Beam Scrapers

Location: WFE/MEBT

General functional requirements:

* Scrape and collimate the beam
* Read collimated current from the scraper jaws to measure halo
* The scraper reading system should be capable of detecting an increase of the current above a user-specified level (accident detection) and sending a corresponding signal to the Machine Protection System (MPS). Reference the Scraper FRS [5] for additional requirements.

Table ‑. Adjustable Beam Scraper Parameters

|  |  |
| --- | --- |
| Parameter | Value |
| Beam energy | 2.1 MeV |
| Beam diameter, rms., typ. | 1 to 4 mm |
| Average Maximum Beam Power | 75 W per plate / 200 W total |
| Transverse positioning resolution | 200 m |
| Transverse positioning accuracy | 1 mm |
| Stroke size for each jaw | ±15 mm |
| Current read out from each jaw | Yes |
| Bias | 0 to +100 V |
| Maximum readout current | 100 μA |
| Resolution of beam current readout | 1 μA |
| Desirable typical scan time | <5 min |
| Operational temperature | +15 to +30 ºC |

### LEBT Invasive Pickups

Location: WFE/ LEBT

General functional requirements:

* Measure instantaneous current of pulsed beam, relative to a beam event, for SCL tuning, operations, and MPS

Table ‑. LEBT Invasive Pickups Parameters

|  |  |
| --- | --- |
| Parameter | Value |
| Beam energy | 30 KeV |
| Beam pulse length | DC to 550 s |
| Intensity resolution | ±1 % |
| Intensity accuracy | NA |
| Beam aperture | 30 mm |
| Operational temperature | +15 to +30 ºC |

### MEBT Invasive Pickups

Location: WFE/MEBT

General functional requirements:

* Measure instantaneous current of pulsed beam, relative to a beam event, for SCL tuning, operations, and MPS

Table ‑. MEBT Invasive Pickups Parameters

|  |  |
| --- | --- |
| Parameter | Value |
| Beam energy | 2.1 MeV |
| Beam pulse length | 10 μs to 550 s |
| Intensity resolution | ±1 % |
| Intensity accuracy | NA |
| Beam aperture | 50 mm |
| Operational temperature | +15 to +30 ºC |

## Beam Loss Monitors

Beam loss monitoring is an important tool for beam tuning as well as a critical part of machine protection. The PIP-II beam loss monitoring system will also help to prevent excessive activation of materials. In general, the current acceptable beam loss limit for SCL is 1 W/m. PIP-II will utilize three types of Beam Loss Monitor (BLM) devices through the SCL and the SCL-to-BTL. The primary BLM devices will be ionization chambers. Ionization chambers have a relatively good response time (few μs), are simple in design and are resistant to radiation damage. The other two BLM devices will be fast Photomultiplier Tube (PMT) based detectors and neutron detectors. These devices generally have a much fast response (~10 to 100 ns).

Diamond detectors and total loss monitors are considered as additional loss monitors. Signal from diamond detectors can serve as input for MPS while total loss monitors can be used as tuning diagnostics and input for the personnel protection system (a radiation interlock). In addition, exact requirements for the diamond detector will be covered within the scope of the MPS. The decision to include the two new types of detectors in the scope of the project will be made based on MARS Monte-Carlo simulations and results of experimental tests with beam at PIP2IT.

Accurate information on beam losses along the SCL readily available to operators is critical for SCL transport tuning. To provide information adequate for accelerator tuning the resolution of loss detection should be better than 0.1 W/m. The refresh rate of measured losses should not be smaller than 1 Hz.

To protect the accelerator from damage in a case of catastrophic accidental beam loss the response of the MPS system, including loss monitors, should be of the order of 10 μs - 20 μs. Exact requirements on the MPS beam inhibit time are defined in the MPS PRD [6].

Beam loss monitors will be located in places of likely losses to ensure their sensitivity to beam losses. Such places are focusing elements between LB650 and HB650 cryomodules and along the BTL beam transport tile line and drifts between SSR cryomodules. Maps of radiation dose induced by beam losses will be simulated using the MARS Monte-Carlo code. Based on these simulations, parameters of beam loss monitors and their exact location will be selected.

### Ionization Chambers

Location: SCL, BTL

General functional requirements:

* Detect loss
* Provide signal to the control system
* Provide input to MPS

Table ‑. Ionization Chamber Parameters

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal beam | Commissioning Beam |
| Detection time | <5 μs | <5 μs |
| Detection threshold | 105 particles/cm2/s | 105 particles/cm2/s |
| Input to MPS | Yes | Yes |

### Photomultiplier Tube (PMT) Loss Monitors

Location: WFE and SRF SCL

General functional requirements:

* Detect loss
* Provide signal to the control system
* Provide input to MPS

Table ‑. PMT Parameters

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal beam | Commissioning Beam |
| Detection time | <100 ns | < 100 ns |
| Detection threshold | 103 particles/cm2/s | 103 particles/cm2/s |
| Input to MPS | Yes | Yes |

### Neutron Detectors

Location: WFE, SCL

General functional requirements:

* Detect loss
* Provide signal to the control system
* Provide input to MPS

Table ‑. Neutron Detector Parameters

|  |  |  |
| --- | --- | --- |
| Parameter | Nominal Beam | Commissioning Beam |
| Detection time | 100 ns | 100 ns |
| Detection threshold | 100 neutrons/cm2/s | 100 neutrons/cm2/s |
| Input to MPS | Yes | Yes |

# Reference Documents

|  |  |  |
| --- | --- | --- |
| # | Reference | Document # |
|  | PIP-II Global Requirements Document (GRD) | ED0001222 |
|  | PIP-II Parameters Physics Requirements Document (PRD) | ED0010216 |
|  | PIP-II Lattice Files | PIP-II DocDB #119 |
|  | PIP-II Vacuum Physics Requirements Document (PRD) | ED0010228 |
|  | MEBT Scraper Functional Requirement Specification | ED0001306 |
|  | PIP-II Machine Protection System PRD | ED0010232 |
|  | “Bunch shape monitors for modern ion SCLs.” S. Gavrilov, A. Feschenko and D. Chermoshentsev, JINST, Vol 12, (2017) | - |