PIP-II AccU-BSTR -Dampers-CHG0

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 functional and technical 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

This PRD addresses the physics requirements of the new Booster Beam Current Monitor (BCM) systemof the **AccU – Booster-Damper-CHG0 Task**, 121.05.04.04.03 PIP-II Project. The main purpose of this task is to replace the existing B:CHG0 with a detector with a higher charge range to accommodate the continued increase in cycle intensity and to provide for a finer resolution and linearity due to the strict requirement for increased acceleration efficiency to the 98% range for PIP-II.

Consequently, this PRD is consistent with the overarching PIP-II Parameters Physics Requirements Document (PRD) [3].

# REFERENCE

|  |  |  |
| --- | --- | --- |
| # | Reference | Document # |
| 1.
 | PIP-II Project Assumptions | PIP-II docDB 144 |
| 1.
 | PIP-II Global Requirements Document (GRD) | ED0001222 |
| 1.
 | PIP-II Parameters Physics Requirements Document (PRD) | ED0010216 |

# ACRONYMS

|  |  |
| --- | --- |
| BCM | Beam Current Monitor |
| DCCT | DC Current Transformer |
| FRS | Functional Requirements Specification |
| FY | Fiscal Year |
| GRD | Global Requirements Document |
| ISD | Interface Specifications Document |
| PIP-II | Proton Improvement Plan II Project |
| PRD | Physics Requirements Document |
| TRS | Technical Requirements Specification |

# ASSUMPTIONS AND DEFINITIONS

* Key cost, schedule, technical and programmatic assumptions are provided in PIP-II Project Assumptions [2].
* Resolution, or precision, is associated with the standard deviation of many measurements. Examples include quantization error of data acquisition as well as measurement errors caused by non-gaussian noise sources.
* Accuracy refers to a systematic offset from the ideal condition or set point, often when averaged over many measurements. Examples are scaling and calibration errors as well as systematic offsets due to timing or operational modes.

# OVERVIEW

The Proton Source through PIP-II Accelerator Upgrade task is replacing the current B:CHG0 detector and electronics with commercial Beam Current Monitor (BCM) system. The main purpose of this replacement is to provide a detector with a higher charge range to accommodate the continued increase in cycle intensity and to provide for a finer resolution and linearity due to the strict requirement for increased acceleration efficiency to the 98% range for PIP-II.

It is desired to install the detector in the tunnel and cables to the gallery during the 2021 Summer shutdown. The 14-week lead time for the detector means the detector needs to be ordered as soon as the PIP-II project obtains CD-3A.

The front-end electronics, distribution electronics, and ACNET interface will be assembled and commissioned post shutdown during FY22.

# BOOSTER BEAM PARAMETERS

## Bunch Structure

In the current mode of Booster operation, PIP, the 400 MeV Linac beam with synchronized notches is injected up to about 17 turns with almost no RF voltage turned on. The beam is then adiabatically captured in about 250 μs. By the end of the capture of this multi-turn beam, a notch of about 3 Booster RF buckets is created. Booster is then left with an almost equally populated 81 bunches.

During the PIPII era, the injected beam will not be adiabatic capture. Instead, the beam will be injected either on-energy or off-energy inside pre-opened Booster RF buckets with a peak voltage of ~0.2 MV and 81 consecutive bunches. Three buckets are left unfilled to form a notch. Each bunch profile will have a local minimum at the center of the bunch in its distribution. Its purpose is to minimize the longitudinal space charge effects at injection. Therefore, the expected bunch structure will be quite different from PIP operations.



Figure ‑. The left figure shows measured bunch pattern for seven bunches at the end of capture for 5.7e12 protons whereas the right pictures shows the predicted bunch pattern at the end of injection during the PIPII era.

## Beam Currents

The typical currents in Booster after injection are between 70 mA to 800 mA depending on the mode of operations. However, due to the bunch structure, the instantaneous peak currents can be as much as 20A in PIPII going through transition.

The peak current depends inversely on the bunch length. In the process of beam acceleration from injection energy to extraction energy of 8 GeV in the Booster, beam goes through transition at 5.16 GeV where the bunch length reaches its minimum just after this energy. Consequently, the peak current reaches its maximum here.

For bunches with a Gaussian profile, the peak current, is given by, where is the RMS bunch length in seconds.

|  |  |  |
| --- | --- | --- |
|  |  |  (1) |

Estimations of are listed in Table 4 at injection and transition energies along with the measured and simulated parameters. Since the bunches at injection do not resemble Gaussian bunch profiles for the PIPII scenario, the following formula is used

|  |  |  |
| --- | --- | --- |
|  |  |  (2) |

The simulations for PIPII shows that as the beam is accelerated, the bunch profiles change and can be approximated as a Gaussian near transition energy.

Table ‑. Calculated PIP and PIPII Peak Currents

|  |
| --- |
| PIP: measured Booster cycle beam data for 5.7e12 protons |
|  | Revolution period (μs) | RMS bunch length (nsec) | Full bunch length (nsec) | Number of protons per bunch | (A |
| Injection (400 MeV) | 2.217 | 4.73 | 20.2 | 7e10 | 0.95 |
| Transition (5.16 GeV) | 1.608 | 0.56 | 3.2 | 7e10 | 8 |
| PIPII: simulated Booster beam data for 6.7e12 protons |
| Injection (800 MeV) | 1.879 | 3.3 | 16 | 8.27e10 | 2.5 |
| Transition (5.16 GeV) | 1.608 | 0.3-0.6 | 2.2-3.2 | 8.27e10 | 18.9[[1]](#footnote-2) |

Table ‑. Booster PIP and PIPII Beam Parameters

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | PIP | PIPII | Units |
| Average Injection Current for tuning per pulse | 36 (~2 to 3 turns, 0.5 e12 protons) | 36 (~18 turns, 0.5 e12 protons) | *mA* |
| Maximum Average Current at extraction per pulse | 700 (7e12 protons) | 800 (8e12 protons) | *mA* |
| Typical number of turns | 2 – 17 | 1 – 300 |  |
| Ramp rate | 15 | 20 | *Hz* |
| Harmonic number | 84 | 84 |  |
| Extraction notch size | 3 | 3 | *Booster buckets* |
| Injection frequency | 37.8 | 44.7 | *MHz* |
| Injection revolution frequency | 450.0 | 532.1 | *kHz* |
| Extraction frequency | 52.8 | 52.8 | *MHz* |
| Extraction revolution frequency | 628.6 | 628.6 | *kHz* |
| Injection kinetic energy | 400 | 800 | *MeV* |
| Extraction energy | 8 | 8 | *GeV* |

# REQUIREMENTS

The new Booster Beam Current Monitor (BCM) system consists of 2 main parts: noninvasive pickup and a set of electronic modules . The pickup shall comply with the requirements for installation into the Long10 straight of the Booster ring. Also, the electronics shall comply with the requirements for installation into the Booster Gallery as well as signal interfaces to other subsystems. FRS, TRS, and ISD documents shall specify additional physical, vacuum, environmental, data acquisition, signal processing and subsystem interface requirements.

The Booster BCM system shall provide beam current measurements throughout the Booster ramp at rate up to 20Hz. Furthermore, these measurements will be used to measurement injection, transfer, and extraction efficiency as the beam enters, accelerates, and then leaves the Booster ring. Consequently, the performance requirements are stringent because the losses in the Booster have to be carefully controlled. The transfer efficiency from injection to extraction is expected to be in the 98% range during the PIPII era and so the beam current measurement accuracy will have to better than 0.1% for the entire Booster ramp.

Furthermore, calibration of these beam current pickups is critical to maintain accurate measurements. A semi-automated calibration system will be utilized allowing for minimal downtime for calibration and/or maintenance.

## DCCT Parameters

The pickup of the Booster BCM system shall be a commerical DC Current Transformer (DCCT). The table below lists the key DCCT parameters.

Table ‑. DCCT Parameters

|  |  |  |
| --- | --- | --- |
| Parameter | Value | Units |
| Minimum Current | 10 | mA |
| Maximum Current | 1 | A |
| Response Time | 50 | s |
| Analog Signal Bandwidth | 10 | kHz |
| Linearity error | < 0.1 | % |
| Output Resolution | < 0.5 |  |
| Output accuracy | 0.1 | % |
| Minimum Beam Aperture | 3.25 | in |

## NPCT Accuracy

The Booster BCM system shall be designed to utilize the Bergoz in flange NPCT sensor and accompanying electronics. The expected accuracy of the “very high-resolution” Bergoz NPCT model during the PIPII era is calculated here. Using the vendor-published specifications, this model has the following current noise spectral density

|  |  |  |
| --- | --- | --- |
|  |  |  (1) |

The NPCT bandwidth of the electronics is kHz. Note that for PIPII, the revolution frequency is 532 kHz at injection. This means that an accurate value of the current is only available after

|  |  |  |
| --- | --- | --- |
|  |  |  (2) |

The noise power, , given both the current noise spectral density, , and bandwidth, , is

|  |  |  |
| --- | --- | --- |
|  |  |  (3) |

The rms noise current, , is thus

|  |  |  |
| --- | --- | --- |
|  |  |  (4) |

In PIPII, the number of protons per injection is mA, thus the fractional error is

|  |  |  |
| --- | --- | --- |
|  |  |  (5) |

which is outside the required 0.1% accuracy.

To achieve the required 0.1% accuracy, the current will have to increase. Let be the number of turns that in Booster that is required to achieve this accuracy, i.e.

|  |  |  |
| --- | --- | --- |
|  |  |  (6) |

The typical number of turns in PIPII injection is about 260. This means that after 25 turns or 10% (25 turns/260 turns) of PIPII will not meet the accuracy specifications. However, from Eq.(2), due to the 10 kHz bandwidth, an accurate measurement of the beam current is only available after injecting 53 turns out of 260 turns, or after about 20% of the injections.

1. Equation (2) used here. [↑](#footnote-ref-2)