Fermi National Accelerator Laboratory

Fermilab

Booster Intensity AIP for PIP-I+ Functional Requirements Specification

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Document Approval

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Revision History

Revision	Date of Release	Description of Change
A		Initial release

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1. Purpose

An FRS describes the programmatic or project needs and/or requested behavior of a system or component. The document 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.

This FRS documents functional requirements for needed upgrades to the Booster sub-systems WBS element. Since PIP-I+ is the transition piece to PIP-II, the problems identified and solved in PIP-I+ in beam physics will be applicable to the success of PIP-II.

2. Scope

This FRS addresses the functional requirements of

i. The Booster two stage collimator (2SC) design, fabrication, assembling on a test bench, testing all its movable parts, installation in the Booster ring and commissioning with proton beam by localizing the beam losses in the collimator units.
ii. Upgrades to the Booster transverse damper circuit boards that includes design, specification, procure damper pickups, fabrication, assembling on a test bench, testing their functionality, implementation in the accelerator system, commissioning of the transverse dampers, necessary software development, commissioning of the transverse dampers.
iii. Upgrades to the Booster longitudinal damper that includes procurement of the cavity, cavity amplifier, damper board design, specific firmware, fabrication, assembly on a test bench, testing their functionality, implementation of the accelerator control system, installation of the damper cavity in the Booster ring, installation of the amplifier, commissioning with high intensity beam.
iv. Specification for the CHG0 intensity monitor, procuring the CHG0 intensity monitor, testing, installation in the ring and commissioning.
v. Beam Physics: Full-ring beam simulations and beam measurements as the upgrade progresses. Beam physics studies will also help identify improvements to the LLRF that was limited by the technology available from the 1970s. Iterate back and forth between transverse and longitudinal beam dynamics issues as new hardware (mentioned above) are installed in the ring as a part of PIP-I+.

3. Acronyms

FESHM	Fermilab ES&H Manual
FRCM	Fermilab Radiological Control Manual
FRS	Functional Requirements Specification
L2	WBS Level 2
L3	WBS Level 3
PIP	Proton Improvement Plan
PIP-I+	Proton Improvement Plan I+ AIP
PIP-II	Proton Improvement Plan -II
2SC	Two Stage Collimator

CHG0	Charge zero detector
DCCT	Direct current Transformer
SCD	System Configuration Document
HLRF	High Level RF
LLRF	Low Level RF
HEP	High Energy Physics
ppp	protons per pulse
TC	Teamcenter
WBS	Work Breakdown Structure

4. Reference

#	Reference	Document #
1	PIP Design Handbook	Beams-docs-4053 (2012)
2	Fermilab Engineering Manual	NA
3	Fermilab Environmental Safety and Health Manual	NA
4	Fermilab Radiological Control Manual	NA
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5. Key Assumptions

Conventional utilities (painting, lighting, fire protection, sump/drainage, impediments) cable trays and work on penetrations will be outside the scope of this FRS and completed prior to 2SC, damper and CHG0 detector installations. Any M&S cost related to acquire/running computer programs for beam simulations, upgrading computers hardware and computer software, purchasing any material supplies are also outside the scope of this FRS.

6. Functional Requirements

Inject 5.2E12 protons per Booster cycle from the current 400 MeV LINAC by multi-turn injection and extract 4.93E12ppp from the Booster at 8GeV with longitudinal emittance of 0.1 eVs and normalized transverse emittance of 16 π-mm-mr at the completion of PIP-I+.

A. 2SC System:
   i. Injection is 14 – 18 turn injection depending on the LINAC beam current to achieve 5. 2E12ppp.The 2SC system should be able to collimate and remove the hallow particle coming from the LINAC.

ii. At 4.5E12 ppp injected beam in the current operation there is about 6% beam loss from injection to extraction. This loss will be increased to about 7% at PIP-I+ intensity. Majority of this loss happens during the first 5 ms of the cycle. The FRS for the 2SC system is to confine 10 – 15% of the total loss in the collimator.
iii. The prompt radiation above the surface should be in accordance with FRCM.
iv. The ground water contamination should be in accordance with FRCM.
v. The radiation at contact should be in accordance with FRCM.

B. Transverse Damper:
   i. Presently, Booster beam (4.5E12 ppp at injection) is made stable by operating at high chromaticities ~-20 units at injection which is at its limit. However, lowered chromaticities lead to beam instabilities because of the reduction in Landau damping.
   ii. It is well known that lowered chromaticities will lead to better lifetime. However, lowered chromaticities lead to beam instabilities because of the reduction in Landau damping. The transverse damper will help mitigate the transverse instabilities and reduce the beam loss associated with transverse instability in the first 5 ms after injection. The FRS for the transverse damper is to reduce the loss 1 – 5% of the total loss.
C. Longitudinal Damper:
   i. Presently, Booster beam (4.3E12 ppp after transition crossing) is made stable by using longitudinal damper. But, longitudinal coupled mode instabilities limit beam intensity. Coupled bunch mode-2 is not presently taken care of because the damping cavity does not have good response for this mode.
   ii. The FRS for the longitudinal damper is to reduce the loss 25 – 30% of the total loss.
D. CHG0 Detector:
   i. The response of the current toroid based CHG0 detector is non-linear at higher beam intensities and has outdated electronics. As intensities go up, the response droops down around 3 ms in the cycle and then recovers later in the cycle.
   ii. New CHG0 detector is a DCCT with enough bandwidth to measure beam intensity beyond 6.5E12ppp in the Booster.
E. Beam Physics:
   i. Beam physics effort during PIP in the transverse plane produced an accurate MADX lattice compared to the past. The as found Booster HEP lattice was found to be not periodic. Well understood periodic lattice is known to improve beam lifetime with reduced transverse beam loss. However, beam data taken during PIP showed that such a periodic lattice gave poorer efficiency as compared with the operational lattice.
   ii. Beam studies in longitudinal phase space have identified problems with both HLRF and LLRF. Simulations of the behavior of beam in both planes will help us improve the transmission efficiency, decrease transverse and longitudinal emittances. From 2018 beam studies we have identified more areas where the HLRF could be improved. Preliminary simulations showed that a factor of two lower longitudinal emittance can reduce RF operating costs by ~30%. In addition to this, simulations also showed that one can relax on the longitudinal emittance at extraction by about 30% with the use of 1st and 2nd harmonic RF systems for snap bunch rotation. These issues will also be addressed.
   iii. Identify the beam instabilities by simulation and help developing mitigation at higher beam intensities while operating the Booster at higher repetition rate as specified by the PIP-II.

7. Safety Requirements

Engineering, design, fabrication, assembly and tests of the given system shall abide by Fermilab ES&H (FESHM) and all Fermilab Radiological Control Manual (FRCM) requirements.

Any changes in the applicability or adherence to these standards and requirements require the approval and authorization of appropriate authority.

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.