PIP-II Injection into Booster Physics Requirement Document (PRD)

Document number: ED0010242

Document Approval

Signatures Required	Date Approved
Originator: Dave Johnson, Booster L3 Manager	-
Concurrence: Alex Martinez, Integration Coordinator	-
Approver: Ioanis Kourbanis, Accelerator Upgrades L2 Manager	Signed in Teamcenter
Approver: Eduard Pozdeyev, Project Scientist	Signed in Teamcenter

Revision History

Revision	Date of Release	Description of Change
-	11-19-2019	Initial release

Page left intentionally blank.

Table of Contents

1. 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 Functional Requirements Specifications (FRSs) and Technical Requirements Specifications (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.

2. Scope

This document describes the high-level parameters for the Injection into Booster.

3. Acronyms

BTL	Beam Transfer Line
CDR	Conceptual Design Report
FRS	Functional Requirements Specification
GRD	Global Requirements Document
L2	WBS Level 2 System
L3	WBS Level 3 System
MEBT	Medium Energy Beam Transport
PIP-II	Proton Improvement Plan II Project
PIP2IT	PIP-II Injector Test Facility
PRD	Physics Requirements Document
RF	Radio Frequency
RMS	Root Mean Square
SRF	Superconducting Radio Frequency
TRS	Technical Requirements Specification

4. Overview

In the PIP-II configuration, the beam will be injected into the Booster from the PIP-II SRF Linac. To reduce the impact of the space-charge the PIP-II beam energy was increased to 800 MeV. To further reduce the impact of the space charge and losses related to the beam capture in RF buckets, injection will utilize a micro bunch-to-bucket, multi-turn, charge-exchange injection into the Booster utilizing both transverse and longitudinal phase space painting procedures. To achieve and maintain the Linac beam quality required for the painting, the PIP-II beam current was reduced to 2 mA and the pulse length was increased to roughly 550 μs.

The new injection scheme requires a new injection region in the Booster as described below. To satisfy programmatic requirements, the Booster will operate at 20 Hz, shortening the Booster magnetic field cycle to 50 ms.

5. Description of the injection section

The 800 MeV Linac beam injected into the newly re-configured Booster Long 11 injection insert (6.68 m length, flange-to-flange, see Figure 5-1) which includes: 1) a vertical closed orbit four-bump in the vertical plane, 2) a stripping foil system, 3) an injection waste beam absorber all within the straight section, and 4) a full field multi-harmonic corrector. A closed orbit painting magnet system, consisting of four horizontal and four vertical painting magnets is located outside the straight section.

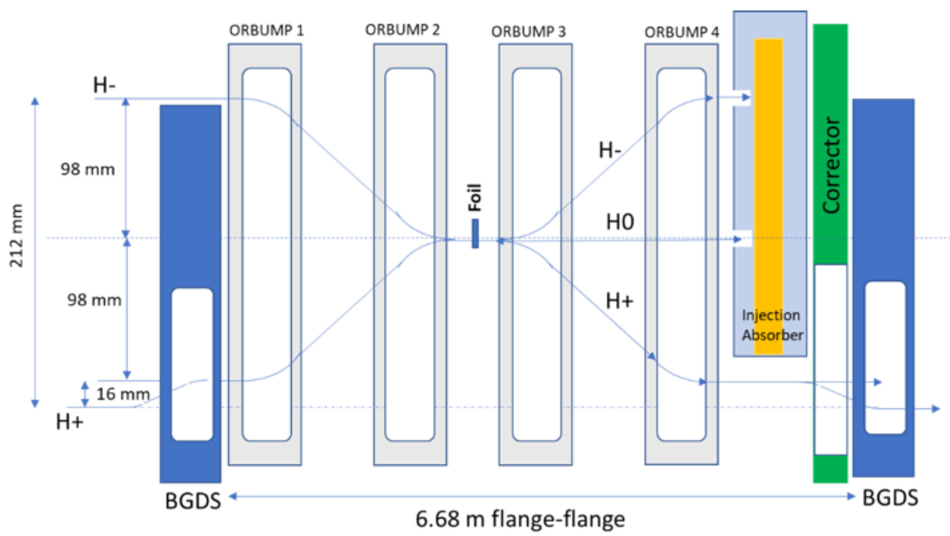

Figure 5-1. Booster Long 11 Injection Insert

A waste beam absorber is required to intercept the unstripped neutrals and any H^- that miss the foil. The injection beam absorber will be installed after the last ORBUMP magnet due to the lack of space required to transport the beam to an outside area.

The length of the injection straight section must be increased to accommodate the injection system while keeping the remaining twenty-three straight sections unchanged. This is achieved by means of reducing the length of the “D” gradient magnet on either side of the straight while keeping the bending angle and the integrated gradient unchanged. The length of the rest of the Booster magnets will remain unchanged.

6. Requirements

6.1. General requirements and considerations

- The Booster will include four horizontal and four vertical painting magnets. The magnetic field in the painting magnets will be controlled using a pre-programmed time-dependent profile, sending the reference beam orbit on a specific pre-programmed trajectory thus creating the desired painted distribution. The field profile in each magnet has to be independently programmable to enable different painting schemes.
- The longitudinal painting is achieved by continuous injection of Linac bunches off the synchronous phase in a Booster bucket. To control the longitudinal injection process and avoid longitudinal losses from particles missing the stable area, the injection system is required to inject Linac bunches that fit a pre-defined phase window (range) or several phase windows (ranges) relatively to a Booster bucket and remove bunches that do not fit the windows using the fast bunch-by-bunch MEBT chopper. The range or ranges of phase values suitable for injection shall be programmable and adjustable by an operator to optimize the final injected distribution.

6.2. Booster injected beam property requirements

- Transverse Emittance: The requirement for the painted transverse emittance is determined by the maximum transverse emittance that the Recycler can accept. The accepted value is a 95% emittance of 16 π-mm-mr. The current Booster has a measured value of emittance growth (at an intensity of ~4E12) during the acceleration cycle of ~60 to 70% assuming no space charge. Assuming the same ratio of the emittance growth for PIP-II, the painted emittance at the end of the injection should be ~10 π-mm-mr. It is expected that PIP-II will demonstrate less emittance growth because of the higher injection energy and a smaller Laslett tune shift. Therefore, the painting scheme should be able to inject the beam into the Booster with the final transverse emittance in the range of 10 to 16 π-mm-mrad.
- Longitudinal emittance and bunch distribution: The longitudinal distribution is obtained through longitudinal painting as described above. The injected longitudinal distribution will be optimized to reduce the transverse space charge at injection, the longitudinal emittance growth during acceleration, and losses during injection and acceleration. The optimization is achieved through the selection of the phase range or ranges in which Linac bunches are injected into the booster and the injection energy offset. The PIP-II CDR [2] presents the results of simulations of the Booster injection using off-center energy injection and anticorrelated transverse painting. The resulting 95% emittance of the longitudinal distribution is 0.06 eV·s. The 95% emittance of the

longitudinal distribution at extraction from the Booster should not exceed 0.1 eV·s. An alternative "on-energy" injection scenario is proposed [3] which is less sensitive to injection field and momentum errors. The final longitudinal emittance of this distribution is also 0.06 eV·s.

- Transverse space charge tune shift parameter: The maximum space charge tune shift is determined by the beam intensity, beam energy, the painted transverse distribution, and the longitudinal charge density distribution (i.e. bunching factor) of the painted distribution. Simulations of the beam dynamics in the Booster show that the space Laslett tune of -0.17 for N_p = 6.5E12, roughly a factor of 2.5 smaller than the tune shift for the existing injection multi-turn injection utilizing longitudinal adiabatic capture with N_p = 4.5E12.

6.3. Matching and regulation requirements

- Beam Transfer Line lattice parameters at the foil location: To minimize the number of foil hits by the circulating beam, the lattice functions of the Linac are mismatched relative to the ring according to:

$$\frac{\beta_L}{\beta_B} \geq \left(\frac{\varepsilon_L}{\varepsilon_R}\right)^{\frac{1}{3}}$$

where subscripts *L* and *B* stand for PIP-II Linac and Booster parameters respectively. The value of this parameter determined by simulations [2], assuming no emittance growth during the acceleration process, is 0.483. If transverse emittance growth is present during the acceleration process, the painted injected emittance must be reduced, hence the ratio of beta functions must become larger.

- The dispersion and it's derivative (both planes) of the Beam Transfer Line (BTL) at the foil should be zero to eliminate motion at the foil due to energy.
- Momentum matching between the Linac and the Booster: The total beam momentum error consists of the Linac error and the Booster synchronous momentum error caused by the Booster magnetic field error. The maximum allowable total momentum error depends on details of the injection scheme and the Booster voltage. Assuming the on-energy injection described in [3], the maximum momentum error dp/p shall not exceed 2.5E-4 RMS.

    - The simulation results of the beam dynamics in the Linac [4] show that the Linac momentum error can be controlled down to 1E-4 RMS
    - The condition of the constant RF frequency and the constant revolution frequency imposes a relationship between the Booster magnetic field error and the corresponding synchronous momentum error:

$$\frac{\delta p}{p} = \frac{\gamma^2}{\gamma^2 - \gamma_t^2} \frac{\delta B}{B}$$

where γ, γ_t is the relativistic gamma-factor at injection and transition, respectively. The coefficient in front of dB/B is -0.13 for the PIP-II Booster injection. That is, the momentum error roughly is a factor of 7 smaller than the field error that causes it. Thus, the effect of Booster field errors on the synchronous momentum is small if field errors are smaller than 1E-3 r.m.s.

- Quadratically added Linac and Booster momentum errors do not exceed the maximum momentum error of 2.5E-4

- Booster magnetic field stability: In addition to the synchronous momentum, Booster magnetic field errors affect the closed orbit. The combined impact on the orbit is given by:

$$x = \eta \frac{\gamma_t^2}{\gamma^2 - \gamma_t^2} \frac{\delta B}{B} .$$

where η is dispersion function. The orbit deviation causes an increase in the beam emittance and increase in the number of the secondary foil hits. Limiting the RMS emittance growth to less than 10% and the orbit deviation to 20% of the distance between the nominal Booster orbit position and the Linac beam spot on the foil, one obtains the limit on the field error: 2.5E-4 RMS.

6.4. Injection efficiency and loss effects and requirements

- Injection foil stripping efficiency: The stripping efficiency is dependent of foil thickness. The foil thickness is a trade-off between stripping efficiency and loss from parasitic hits and is a subject for optimization. The results presented in the CDR show that a foil thickness of 600 g/cm^2 is a reasonable compromise between the stripping efficiency and the number of parasitic hits and foil heating.
- Lorentz stripping: The ORBUMP injection magnets will strip the injected beam activating the injection section. The magnetic field of the ORBUMPS has to be optimized along with the absorber and the geometry of the injection section to reduce activation of components.
- Losses from parasitic hits from circulating beam during painting: Those include large angle Coulomb scattering and nuclear scattering.
- Loses due to H0 excited state stripping: The ORBUMP magnetic field downstream of the foil determine the number of ions in excited Stark states and the lifetime of these states. The result is that the upper excited stated strip inside the magnet resulting in a proton with a smaller bend angle than the protons created by the foil which either contribute to the circulating phase space, halo, or lost on downstream apertures.
- Loss load on injection absorber: This is a combination of stripping efficiency and H- missing the absorber. Due to space constraints, the limit on the absorber load is determined by the radiological limits of prompt dose outside the berm, isotope production in the soil, and residual activation of the absorber and the corrector immediately downstream of the absorber.

- Residual intensity left in the extraction notch: This is one of the factors that will determine extraction loss in addition to the vertical transverse emittance. The maximum allowed loss at extraction depends on other sources of loss. Currently, it is hoped the extraction loss from all sources to be less than 0.02% or 36 Watts.
- Residual intensity in chopped Linac bunches not captured in Booster bucket: Bunch chopping in PIP2IT demonstrated that the residual intensity after bunch chopping did not exceed 0.1% of the original intensity. The minimum measured intensity was limited by the resolution of instrumentation. If 60% of the Linac RF bunches are removed from the Linac RF buckets and they are removed to the 1e-3 level, this will equate to about 1.32 J outside the bucket on each injection or at 20 Hz about 26.37 Watts to be lost in the ring (at the smallest aperture at the start of acceleration.

6.5. Summary of requirements

Table 6-1 summarizes the Booster injection requirements. Requirements denoted by * are subject to revision pending additional detailed simulations and tracking.

Table 6-1. Summary of Booster Injection Requirements

Parameters	Value	Units
Injection Parameters		
Injection intensity	6.7	10^{12}
Number of turns for injection, approx.	285	-
Injection time, approx.	538	us
Final painted 95% transverse emittance	10-16	π-mm-mrad
Final painted 95% longitudinal emittance	.06	eV-sec
Injection foil thickness (current value)	600	g/cm^2
Injection Twiss Functions on foil		
Mismatch ratio, β_L/β_B, for final painted trans. Emittance*	0.483	-
β_x	2.98	meter
α_x	-0.046	-
D_x	0	meter
D'_x	0	-
β_y	9.67	meter
α_y	-0.014	-
D_y	0	meter
D'_y	0	-
RMS Horizontal beam size at foil, σ_x*	0.7	mm

RMS Vertical beam size at foil, σ_y *	1.3	mm
Horizontal level of collimation in BTL (one side) *	0.5	%
Vertical level of collimation in BTL (one side) *	0.5	%
Horizontal injected beam center from edge of foil *	1.95	mm
Vertical injected beam center from edge of foil *	3.51	mm
Stability Requirements		
Horizontal Position stability *	20	microns
Vertical Position stability *	20	microns
GMPS amplitude stability cycle-to-cycle, rRMS*	$2.5x10^{-4}$	-
Linac momentum jitter dp/p, RMS	$1.0x10^{-4}$	-
Expected Loss		
Due to Lorentz stripping (10^{-6}/m) (ORBUMP 1 & 2)	<17	mW
Loss due to Large Angle Coulomb Scattering (in foil)	~2.5	W
Loss due to nuclear scattering (in foil)	~0.11	W
Loss due to stripping of H0 excited states (ORBUMP 3)	<1 check	W
Maximum Loss load on injection absorber (TBO) *	200	watts
Operational Loss load on injection absorber (TBO) *	30	watts
Loss at acceleration due to chopping inefficiency	26	watts
Loss at extraction due to beam left in extraction gap	6	watts

* - values are to be refined through detailed simulations

6.6. Appendix: Assumed Booster parameters

Table 6-2 shows the Booster Ring parameters.

Table 6-2: Booster Ring Parameters

Assumed Booster Ring Parameters	Value	Unit
RF frequency at injection	44.704	MHz
Revolution frequency	532.193	kHz
Harmonic number	84	-
Filled Booster buckets	81	-
Bucket length (injection)	23.369	ns
Bucket length (extraction)	18.935	ns
Maximum power loss (5 min avg)	500	W
Booster Twiss Parameters at Foil	**Value**	**Unit**

β_x [ideal /as found/used]	6.13/5.87/6.35	meters
α_x [ideal /as found/used]	-0.049/-0.019/0.108	-
D_x [ideal /as found/used]	1.839/1.735/2.234	meters
D'_x [ideal /as found/used]	0/0/0	-
β_y [ideal /as found/used]	20.16/19.5/19.04	meters
α_y [ideal /as found/used]	-0.015/-0.0174/0.0356	-
D_y [ideal /with ORBUMP on]	0/ -0.1164	meters
D'_y [ideal /with ORBUMP on]	0/0	-

7. Reference Documents

#	Reference	Document #
1	PIP-II Global Requirements Document (GRD)	ED0001222
2	PIP-II Conceptual Design Report	PIP-II DocDB #52
3	On Energy Booster Injection Scheme for PIP-II	PIP-II DocDB #4023
4	Beam Dynamics Studies of Misalignments and RF Errors for PIP2	PIP-II DocDB #4083