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BEAM COLLIMATION IN THE PIP-II LINAC TO BOOSTER TRANSFER LINE*

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Abstract

The new PIP-II superconducting linac will deliver a 2 mA average H- beam to the existing Booster synchrotron. The injected beam is accumulated by charge exchange over approximately 300 turns; phase space painting is used to mitigate space charge effects. To limit the power load on the internal waste beam absorber from the transverse tails of the H- distribution missing the foil, the beam will be collimated in both planes in the linac to Booster transfer line using compact collimators of a novel design. Both the number of parasitic hits and the fraction of the beam missing the foil are sensitive functions of the H- beam centroid position with respect to the edge of the foil. The positioning of the collimation is constrained by the availability of suitable space in the transfer line lattice, by specifics of the collimator design, by the phase space orientation at the collimator, and by the betatron phase advance to the foil needed to achieve proper orientation of the spatial distribution at the injection point. In this contribution, we describe the procedure by which collimator positions were optimized. We then discuss the expected performance of the overall system.

INTRODUCTION

The 400 MeV to 8 GeV 15 Hz Booster RCS uses a FODO-like lattice composed of combined function magnets (CFMs) arranged in 24 periods with a circumference of 475 meters. Each period contains a short straight (0.88m flange-to-flange) and a long straight (5.68m flange-to-flange). The lattice may be represented as 24x[F-O-FD-OO-D]. The long straight sections are utilized for injection and extraction systems, collimation systems, kickers for extraction and extraction gap clearing, RF cavities, dampers, and diagnostic equipment. The Booster utilizes multi-turn injection of H- through a carbon stripping foil without phase space painting. Longitudinally, the injected beam shears during injection, then adiabatically captured by the Booster RF system. The current 400 MeV linac is capable of injecting up to a 44 μs linac beam pulse, corresponding to 19 turns in Booster, for an accumulated intensity of 4.5E12 protons/cycle and injected beam power of 4.4 kW. The normalized 95% emittance out of the linac is on the order of 12 π-mm-mr. The limit on the transverse normalized emittance at extraction is 16 π-mm-mr, set by the acceptance of the downstream machine. The Booster currently runs just below the administrative limit of ~1 watt/meter for all losses during the cycle averaged over a 5-minute period.

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PIP-II is constructing an 800 MeV superconducting linac that will operate at 20 Hz rep rate to supply 17 kW of beam power to the Booster. The 162.5 MHz bunch train out of the radio frequency quadrupole (RFQ) has a bunch current of 5 mA. Since the Linac bunch frequency is not a harmonic of the Booster RF frequency at injection, the linac pulse is chopped in the MEBT to allow a micro-bunch to bucket injection into the Booster. To accumulate the nominal PIP-II design intensity of 6.7E12 protons per cycle, an injection period of 535 μs or 285 Booster turns is required.

BOOSTER INJECTION

New Injection Layout for PIP-II

A new Booster injection insert is required for integration of PIP-II into the Accelerator Complex. Due to the increase in injection energy the length of the new injection straight section will be increased by 1 meter by shortening the adjacent CFMs. Figure 1 shows the layout of the elements in the new insert. The vertical pulsed dipoles (ORBUMP) are used as a closed orbit bump to raise the closed orbit to the level of the injection foil. In addition, the first two magnets are used to guide the linac H- beam onto the foil. This insert must contain an injection waste beam absorber and keep the harmonic corrector. Figure 2 shows the lattice functions in the injection and adjacent straight sections.

PIP-II Injection Process

The multi-turn injection from the PIP-II Linac will utilize phase space painting with dedicated magnets outside the straight section. The current plan is to utilize anti-correlated painting with sin and cos waveforms. [1, 2] The goal is to paint to a 95% un-normalized emittance of ~10 π-mm-mr compared to ~1 π-mm-mr for the linac.

Injection Foil

The injection stripping foil is planned to be a self-supporting nanocrystalline diamond foil [3] with a nominal thickness of 600 μg/cm^2. The stripping efficiency for this thickness is expected to be 99.94% indicating that 0.06% of the beam will emerge from the foil as excited states of neutral hydrogen. A small fraction, 0.0048%, of excited states with n > 3 will strip in the downstream ORBUMP magnet contributing to the uncontrolled loss [4]. The remainder, 0.055%, are more strongly bound and will not strip in the ORBUMP magnetic field. These will impact the injection absorber. During the injection process, the passage of the H- through the foil and the injected protons that pass through the foil on subsequent turns (i.e. parasitic hits) will undergo large angle scattering leading to an uncontrolled loss. This loss and its distribution around the ring are under investigation for PIP-II injection [2]. Of

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concern is the uncontrolled loss in the long straight, L12, just downstream of injection as shown in Fig. 2. This straight contains gap clearing and extraction kickers, particularly vulnerable to losses.

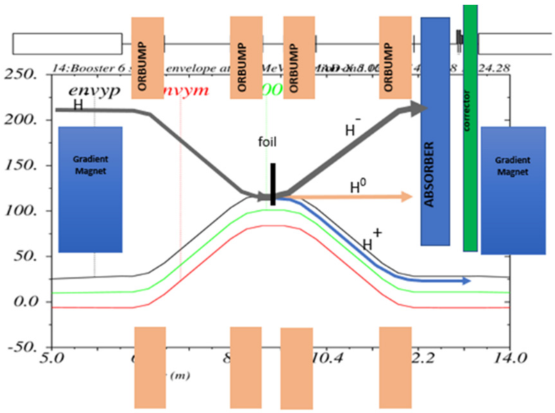

Figure 1: Elevation view of the elements in the PIP-II Booster injection insert.

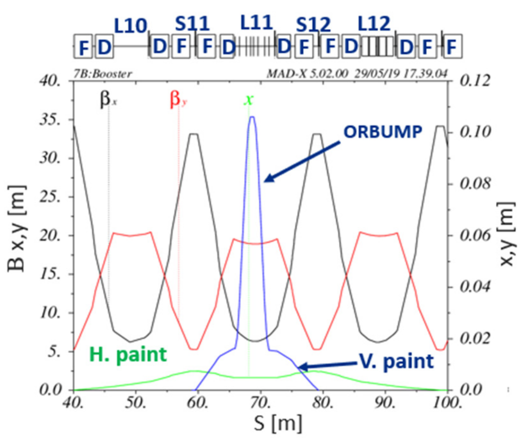

Figure 2: Lattice functions in the injection straight, beamline element layout, the vertical closed orbit bump, and the H & V painting orbits at the start of injection.

The magnitude of the large angle scattering loss is determined by the probability of large angle scattering times the average number of foil parasitic hits per injected proton times the number protons injected. To minimize the foil dimensions and parasitic hits, the injected beam should follow the criteria for mis-matched injection [5]. Following this prescription, the core of the injected beam will be nestled close to the lower inside corner of the injection foil. A few percent of the incoming H- will miss the foil and must be intercepted by an injection absorber. The ideal solution would be to direct the waste beam to an external, well shielded, absorber. Unfortunately, the lattice and tunnel constraints dictate that the injection absorber must be located in the circulating beam line, as indicated in Fig. 1.

Losses

Typically, the areas with the largest residual activation are the injection, extraction, and collimation regions. The activation in the injection is of particular concern due to the required maintenance activities. Therefore, we strive to minimize the activation in this area and other sensitive areas.

The main sources of activation in the injection area have been identified as 1) H- missing the foil dumped in the absorber with >170 watts, 2) Large Angle Scattering from parasitic hits on the foil with few 10's of watts distributed in limiting apertures around the ring, 3) neutrals to the absorber with 10's of watts, and 4) neutrals in Stark states with n >3 stripping in downstream ORBUMP dipole, yielding on the order of 1 watt [4]. Clearly, the dominant contribution to the activation in the injection region is due to the large amplitude H- missing the foil. We investigate removal of these large amplitude particles through collimation in the beam transfer line (BTL) [6].

BEAMLINE COLLIMATION

Positioning the Collimation System

Two criteria must be met for the positioning the collimation system in the BTL. It must fit within the straight section half-cell and since we want a specific orientation of the cut to the transverse distribution, we must orient the collimator primary at a modulo of 180 degrees upstream of the injection foil. Based on the design of the BTL, only the first three cells in the straight section are available for collimator locations. Figure 3 shows the TraceWin [7] 6 σ beam envelope of the entire BTL, from the end of the last cryo-module in the linac to the Booster injection foil. The locations of the two zero-length collimators are shown.

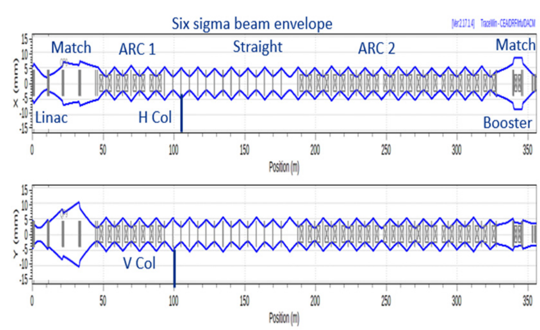

Figure 3: Six-sigma beam envelope from TraceWin showing the location s of the collimators in the beamline.

The phase space and x-y distribution immediately after the zero-length vertical collimator is shown in Fig. 4. This location is modulo ~360 degrees upstream of the foil. The x-y distribution at the injection foil with collimation off and on is shown in Fig. 5. The red lines represent the edge of the foil indicating the level of large amplitude removal to minimize the particles that would otherwise miss the foil. The level of collimation and how close the core can be

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nestled to the foil corner will depend on the position stability of the beam on the foil.

Collimation System Design

A technique for collimation of H- ions uses a thin foil upstream of a focusing quad strips large amplitude intended for removal. [8] The focusing quad focuses the H- but defocuses the protons to impact a downstream absorber at a large impact parameter to minimize out scattering. To increase the flexibility of this method the downstream absorber could have a variable aperture. However, the quad strength and half-cell length of the BTL are not acceptable for application of this method.

A second technique typically used in proton transport lines is that of a scraper and downstream masks. Typical efficiency for containing primary and secondary protons by the single absorber is the 50% level.

An alternative technique is a single plane version of a monolithic two stage collimator (m2SC) being developed for the Booster ring. [9] For this application we utilize a single thick movable copper primary collimator along with a stationary secondary (sSecondary), a variable aperture secondary (mSecondary) with movable jaws, followed by a mask. All components are contained in a single absorber module surrounded by 50 cm of steel followed by 10 cm marble as the external surface as shown in Fig. 6.

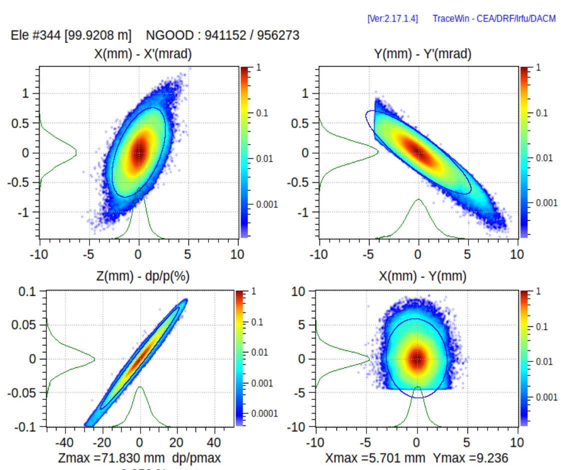

Figure 4: Phase space distribution immediately after the zero-length vertical collimator element.

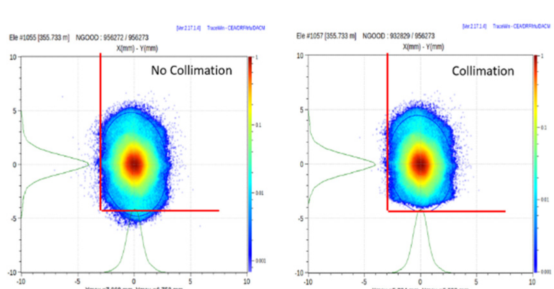

Figure 5: The x-y distribution of the linac beam on the injection foil.

The flange-to-flange length of this module is 4.16 meters. Preliminary MARS simulations as part of a BTL radiation shielding assessment have been performed to look at prompt dose on the surface, ground water activation, tunnel air activation and no unsatisfactory results were obtained [10].

The red dashed lines in Fig. 6 are measurement planes for proton fluxes [1/cm^2/s]. The two figures show the proton flux within the aperture after the primary absorber and at the downstream end of the mask. The proton flux outside the aperture (steel shielding) will create hadron showers.

For the given beam distribution on the primary and a standard offset of Primary (2.5 σ_x) and mSecondary (+/- 2.5 σ_x + 2 mm) from the central orbit, we see very good efficiency in the reduction of protons exiting the aperture.

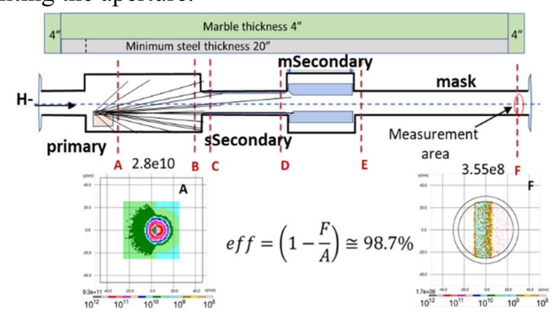

Figure 6: Layout of a single plane monolithic two stage collimator.

CONCLUSIONS

We have proposed a collimation system with the proper phase advance to remove the large amplitude particles from the distribution that would otherwise miss the foil. We used TraceWin to find the proper location. We have a preliminary mechanical design and have performed preliminary radiation transport analysis and efficiency analysis and results look promising. Further study of operational conditions will follow.

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