FERMILAB BOOSTER INJECTION UPGRADE TO 800 MEV FOR PIP-II*

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Abstract

Fermilab is proposing to build an 800 MeV superconducting linac which will be used to inject H^- ions into the existing Booster synchrotron as part of the proposed PIP-II project. The injection energy of the Booster will be raised from the current 400 MeV to 800 MeV. Transverse phase space painting will be required due to the small linac transverse emittance ($\varepsilon_{ring}/\varepsilon_{linac} \sim 10$) and low average linac current of 2 mA. The painting is also helpful with reduction of beam distribution resulting in a reduction of space charge effects. The injection will require approximately 300 turns corresponding to ~ 0.5 ms injection time. A factor of seven increase of the injected beam power (relative to present operation) requires an injection waste beam absorber. The paper describes the requirements for the injection insert, its design, and plans for transverse painting.

THE FNAL BOOSTER

The 40+ year old Booster contains 24 periods and can be described as a FoDooDoF lattice utilizing gradient magnet pairs (FD or DF) mounted on a girder with long straight sections (5.68 meters) between the defocusing gradient magnets and a short straight section (0.5 meters) between the F and D gradient magnets. Horizontal beta function varies from about 6 meters in the long straight to 33 m in the short straights while the vertical beta function varies from 20 m in the long straights to ~5.3 m in the short straights. The horizontal dispersion varies between approximately 1.8 (in the long straights) and 3.6 meters. The "nominal" ring optics is shown in Fig. 1.

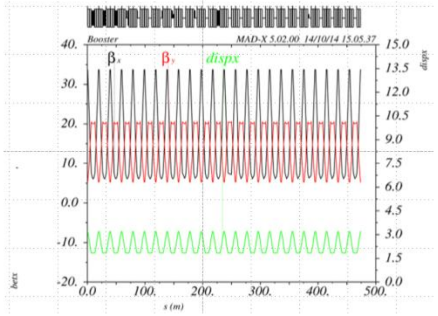

Figure 1: Booster lattice functions.

The current injection insert is located in one of the long straight sections (Long 1). The injection [1,2] is based on a three dipole (powered by a single supply) horizontal orbit bump moving the closed orbit by about 45mm onto a carbon stripping foil to match a trajectory of injected H^- beam for the duration of injection. The multi-turn injection time is $N_{turns}*\tau_{Booster}$ ~35μs for $N_{turns}=16$. Since the transverse emittance of the current 400 MeV linac is close to the Booster acceptance, no transverse phase space painting is used. Figure 2 shows the lattice functions for the injection straight with locations of the gradient and injection bump magnets shown at the top of the plot and the injection trajectories shown in the inset.

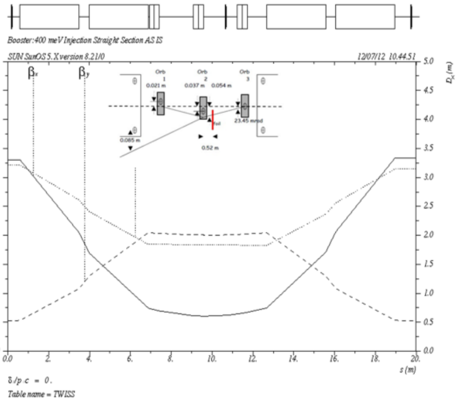

Figure 2: Current Booster injection straight section lattice.

800 MEV INJECTION

The goal of this effort is to verify that we can inject the PIP-II linac beam into the existing Booster at twice higher energy and to find the major issues to be addressed. The major challenges of the new injection system are related to (1) the ability to incorporate a well shielded injection absorber in the current straight section length to handle the factor of 7 increase in injection beam power (17 kW), (2) to introduce a dipole chicane capable to move the closed orbit onto the injection foil, and (3) to support both horizontal and vertical painting based on the control of closed orbit during injection. We also strive to limit the peak field in the single-turn ferrite loaded chicane dipoles to 3 kG due to ferrite saturation near the coils [3].

INITIAL CONCEPTUAL DESIGN

The initial conceptual design for the new injection insert, as described in the PIP-II RDR [4], utilizes an existing straight section (Long 11) with a flange-to-flange length of 5.68 m. The insert is located between gradient magnets and includes a vertical three bump chicane as shown in Fig. 3. The injection stripping foil is located after the two central chicane dipoles. Here, the vertical chicane dipoles not only move the closed orbit onto the foil, but serve as vertical painting magnets as well. The bending angle of each of the chicane dipoles is approximately 40 mrad. Horizontal painting magnets are located in the short straight sections on either side of the injection straight. The last injection line dipole located over the upstream gradient magnet directs the incoming H^- ions onto the foil. As the injected H^- beam passes

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through the varying field of two central bump magnets, this dipole (or a nearby corrector in the transport line) needed to be ramped to compensate the change in the central dipole field required for painting. As can be seen in Figure 3, the injection waste beam absorber can only fit between the last chicane dipole (PM3) and the Booster gradient magnet.

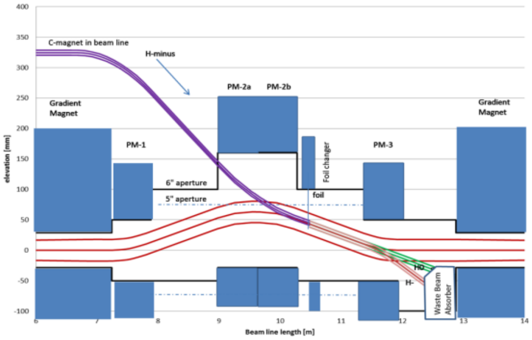

Figure 3: Initial concept for PIP-II injection into Booster.

A preliminary MARS [5] model of this injection layout was developed assuming 400 W waste beam power which includes up of 2% H^- missing the foil and 0.2% H^0. The absorber is made up of a 5 cm x 5 cm x 30 cm tungsten core surrounded by 15cm steel on a concrete pedestal surrounded by marble. Additionally, the upstream and downstream magnets have a 10 cm marble shield on the top and aisle side. An estimate for tritium production in the soil around the injection straight indicated that the shielding is sufficient to avoid this problem. Additionally, estimates of the residual activation on components in the area and absorbed dose in the magnets surrounding the absorber were performed. Figure 4 shows a side view of the model for the absorber area inside the Booster tunnel (left) and the absorbed dose in the adjacent magnets (right). The residual activation on the upstream flange of downstream gradient magnet is about 100 mSv/hr and the absorbed dose in the upstream end of the gradient magnet is about 4 MGy/yr. With typical lifetimes of kapton insulation of 20-30 MGy, it leads to a magnet replacement every 5-7 yrs. – an unpleasant feature due to ALARA issues for magnet replacement and associated cost and machine downtime.

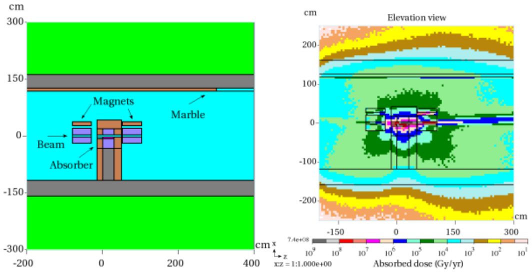

Figure 4: MARS model (left) and absorbed dose(right) after 30 days of irradiation and 1 day cool down.

ALTERNATE CONFIGURATION

It is clear that the desire to utilize the existing length of the long straight section is problematic in terms of proximity of the absorber to the downstream Booster gradient magnet, absorbed dose in adjacent magnets, and residual activation of components.

An alternate configuration is based on a length reduction of the adjacent gradient magnets by ~30%. This increases the straight section length by about 0.86 m. This configuration utilizes a vertical four bump chicane with the foil between the two central chicane dipoles allowing for the waste beam to impact the absorber farther from the aperture of the gradient magnet. It also yields an additional space for the absorber shielding as shown in Fig. 5. With the foil located at the peak of the chicane bump, the strength requirements on the chicane dipoles are relaxed. Additionally, there is room for separate painting magnets (in both planes). Magnet apertures are represented by open boxes.

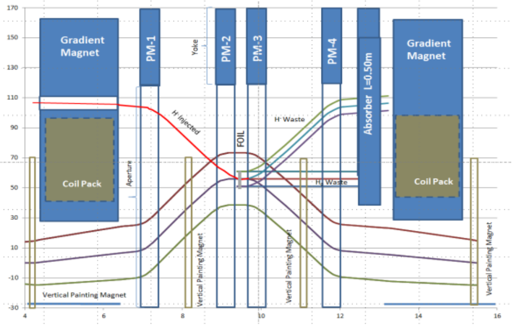

Figure 5: Alternate configuration for injection insert using a vertical 4-bump and separate painting magnets.

A preliminary MARS model for the alternate injection layout was developed. Figure 6 shows the MARS model (left) and the absorbed dose (right). The model includes a 30 cm tungsten absorber (magenta) surrounded by 10 cm steel (gray), the upstream chicane dipole ferrite yoke (red), the downstream gradient magnet yoke (tan) and coils (green). A 10 cm piece of marble (brown) is shown upstream of the gradient magnet. The same beam conditions were used as before to look at the absorbed dose and residual activation. The absorbed dose to the gradient dipole coils is reduced substantially to 0.12 MGy/yr. The residual dose is in the range of 10-100 mSv/hr, still a bit high. Additional optimization is going on.

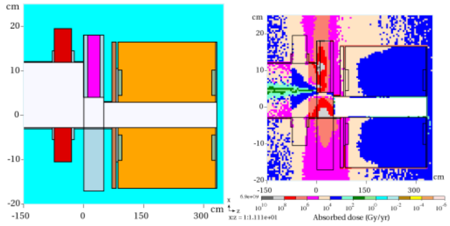

Figure 6: Alternate model configuration of absorber and adjacent magnets(left) and absorbed dose (right).

PHASE SPACE PAINTING

Transverse

Initial simulations of transverse phase space painting have been performed [6,7] for the initial conceptual design. Experimental cross-sections for 800 MeV H^- stripping by carbon foils as a function foil thickness are presented in Ref. [8]. A choice of foil thickness is based on a balance between stripping efficiency and loss due to secondary hits. In the current simulation, vertical phase space painting is performed by the vertical chicane dipoles and horizontal painting was performed using the present horizontal correctors outside the injection straight section. The motion of the closed orbit at the foil is correlated in the H & V planes and proceeds along a quarter of ellipse with 9.5 mm and 5.3 mm semi-axes, respectively. After painting the chicane dipole fields are zeroed. It results in a beam displacement to the nominal closed orbit. To minimize the number of circulating beam hits on the foil, the lattice functions of the injected beam are scaled to create a lattice mismatch [9] so that the linac phase space would be inscribed in the *x*-and *y* machine acceptance. The simulations include multiple scattering in the foil, synchrotron and betatron oscillations and painting details described above. The beam space charge effects are not taken into account and motion is assumed without *x-y* coupling. Figure 7 shows the particle distributions in Courant-Snyder invariants (left pane) and the integrals of the particle distributions (right pane). Here 95% of the particles are within 17 μm and 100% are within 23 μm. Simulations also accumulated primary and secondary hit distributions on the injection foil and found that the peak temperature on the foil to be 640^{o}C at the foil corner, thus foil heating will not be an issue. Details can be found in Refs. [6,7].

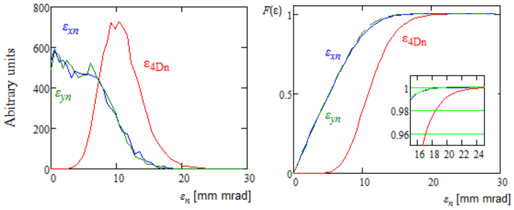

Figure 7: Transverse particle distribution and integral

Longitudinal

The linac bunch frequency of 162.5 MHz is not an integer value of the Booster RF frequency of 44.705 MHz, therefore the injection process is asynchronous. The linac bunches that would arrive outside of the RF bucket will be removed by a pre-programmed bunch-by bunch chopper in the linac MEBT.

Since the momentum spread of the linac beam ($2{\cdot}10^{-4}$) is an order of magnitude smaller than that of the Booster RF-bucket height ($2.2{\cdot}10^{-3}$), longitudinal painting is also required. The injection process duration corresponds to 7 synchrotron periods; consequently, a static longitudinal painting process will be employed. The linac energy is offset relative to the Booster reference energy thus the synchrotron motion will mix the particles in the longitudinal phase space during injection. A value of momentum offset ($7{\cdot}10^{-4}$) was selected to optimize the bunching factor (2.5), as shown in Fig. 8. The left pane shows the longitudinal phase space of the linac beam (with static momentum offset) and the boundary of the Booster RF-bucket. The right pane shows the phase space at the end of injection process.

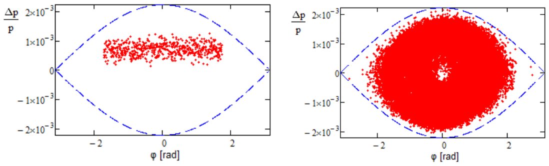

Figure 8: Longitudinal phase space of injected particles (left) and resultant longitudinal phase space at end of injection (right).

The longitudinal particle distribution and its integral are shown in Fig. 9. Here one can see that 100% are contained in the longitudinal emittance of 0.06 eV-sec.

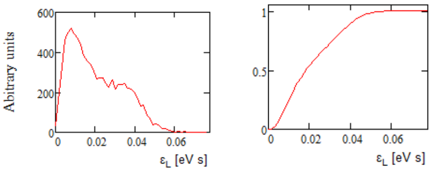

Figure 9: Longitudinal particle distribution and integral

CONCLUSION

We developed two potential injection straight section designs to investigate an impact of internal injection absorber on the surrounding equipment. Although the alternate design requires the design and construction of new, shorter gradient magnets, there is significant gain in the reduction of the absorbed dose and increase in the lifetime of the gradient magnet. We have investigated both transverse and longitudinal painting design and no significant issues have been identified.

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