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6D SIMULATIONS OF PIP-II BOOSTER INJECTION*

J. -F. Ostiguy†, D. E. Johnson
Fermilab, Batavia IL, USA

Abstract

The PIP-II superconducting linac will deliver 2 mA average H^- beam current at 800 MeV to the existing Booster synchrotron over a period of 0.55 ms (285 turns). As a result, the injected beam power will quadruple to 17 kW. Safe operation at the increased beam power implies careful attention to the origin, magnitude, and distribution of both controlled and uncontrolled losses.

Uncontrolled losses are due to neutral ions in excited states stripped in downstream magnets and large angle scattered protons from parasitic foil hits. The relative magnitudes of these loss mechanisms is used to determine the optimal foil thickness.

A transverse painting scheme involving closed orbit motion will be used to mitigate space charge effects and minimize parasitic foil hits. Using a detailed full 6D simulation of the injection process, we compute large angle scattering losses and compare results to back of the envelope estimates. We investigate possible impact of space charge on the emittance and beam distribution both during and at the conclusion of the injection period.

INTRODUCTION

The Proton Improvement Plan-II (PIP-II) is an upgrade to the Fermilab accelerator complex which will provide high-intensity proton beams to support the laboratory's experimental program for the next decades.

The new PIP-II superconducting linac will deliver bunches of H^- ions at 2 mA average to the existing Booster synchrotron at 800 MeV. Accumulation by charge exchange will take place over a period of 0.55 ms (285 turns) at the beginning of each booster cycle. Compared to current operations, the overall injected number of protons will increase by a factor of 1.5; this, combined with an increase in the booster cycle frequency from 15 to 20 Hz and the doubling of the beam energy will result in an overall four times increase in injected beam power to 17 kW.

High intensity operation requires substantial attention to beam losses. These losses belong to two categories: controlled and uncontrolled. Controlled beam loss includes losses occurring in the beam dump or in collimators and can reach somewhat higher level because they are by design, predictable well-localized and managed while uncontrolled beam losses are more problematic. A commonly used guideline is that to allow for hands on-maintenance, uncontrolled losses should be kept below 1 W/m. For a 17 kW beam and a 474 m circumference Booster ring this translates into total uncontrolled losses of a few tens of W.

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† ostiguy@fnal.gov

PHASE SPACE PAINTING

Injection painting is the process of using the significantly smaller injected beam phase space footprint as a "brush" to "paint" a larger phase space area occupied by the circulating beam.

Optimal painting efficiency is achieved when the injected beam ellipse matches the curvature of the ring phase space elliptical contours. Using the subscripts i and r to denote parameters associated respectively to the injected beam and to the ring this occurs if [1]

$$\frac{\beta_r}{\beta_i} = \left(\frac{\epsilon_r}{\epsilon_i}\right)^{1/3} \tag{1}$$

$$\frac{\alpha_i}{\beta_i} = \frac{\alpha_r}{\beta_r} = -\frac{\xi_i'(t) - \xi_o'(t)}{\xi_i(t) - \xi_o(t)} \tag{2}$$

where ϵ is the emittance, $\xi_i = x, y$ and $\xi_o = x_o, y_o$ are respectively the positions of the injected beam and of the closed orbit. The ratio (1), known as the mismatch factor, should be as small as possible to limit the no of parasitic foil hits. The beam is usually injected at a fixed position on the foil i.e. $\xi(t) = \text{const.}$ Note that $\alpha_r \neq 0$ implies that both the closed orbit and the injection angle have to change during injection, which is technically possible but not always straightforward. A simple choice (adopted for PIP-II) is to inject at at location where $\alpha_r = 0$. The injection angle remains tangent to the closed orbit and the numerator in Eq. (2) vanishes. Painting involves moving the closed orbit using bump magnets.

By simultaneously moving the closed orbit in the horizontal and vertical planes in opposite directions i.e. in an anti-correlated pattern, an approximate K-V distribution in transverse phase space can be obtained. Different orbit motion functions are possible; the PIP-II conceptual scheme assumes sinusoidal functions [2].

INJECTION STRIPPING FOIL

Electrons are stripped from H^- ions in collisions within the bulk of the foil material. A small fraction of the ions are not fully stripped. Neutral H^0 ions will be collected in a dump located immediately downstream of the foil. Because they are left in various excited states, uncollected H^0 are likely to get magnetically stripped in the magnetic field of the next downstream bending magnet. High stripping efficiency can be achieved with a relatively thin foil, (99%) and can be improved further by increasing the foil thickness. The allowable thickness is limited by thermal considerations, by degradation in beam quality (due to small angle Coulomb scattering) or by uncontrolled beam loss due to large angle scattering (Coulomb and Nuclear). For the Booster in the PIP-II era, foil heating and emittance blowup due to small

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angle scattering are not primary concerns and the optimal foil thickness represents a compromise between losses associated with neutral ions and losses due to large angle elastic scattering.

SIMULATIONS

The essentials of the PIP-II painting scheme have been established in a simple manner by tracking particles using a linear map and moving the injected beam within the ring phase space. However, to obtain a particle loss pattern or to account for possible space charge effects requires resorting to a full-fledged tracking code. Among the few mature tracking codes available to model injection we settled on `PyORBIT` [3], a close relative of the `ORBIT` code originally developed to model the SNS accumulation ring.

Starting from a detailed MADX description of the Booster 800 MeV optics, a flat element sequence was generated and imported using the `PyOrbit` MADX sequence parser. Good agreement was obtained between the `MADX` and `PyOrbit` lattice functions indicating that the lattice was correctly imported. The lattice includes orbit control magnets, cavities, as well as aperture information for most elements.

Injection Region Layout

Figure 1 is a detail of the injection region. A vertical chicane brings the orbit 97 mm above the reference defined by the adjacent bending magnets centerline. Using painting magnets located upstream and downstream of the injection region, the closed orbit is further moved up to 113 mm above the centerline and horizontally 6.1 mm toward the inside of the ring. During injection the orbit is moved according to the prescription

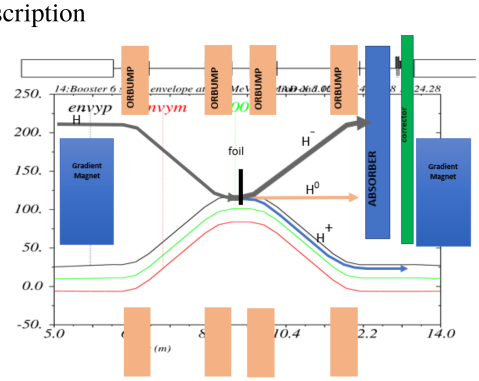

Figure 1: Schematic of the PIP-II Booster injection region. The H^- ions are injected vertically. The vertical orbit is deflected using four orbumps magnets and the beam hits the foil at a fixed location near the inner lower corner of the foil.

$$
\begin{aligned}
x_o(t) &= a \cos\left[\frac{\pi}{2}\frac{t}{T_{\text{inj}}} + \phi_i\right] + D_x \Delta p \\
y_o(t) &= b \sin\left[\frac{\pi}{2}\frac{t}{T_{\text{inj}}} + \phi_i\right] \qquad (3)
\end{aligned}
$$

with $a = 6.1$ mm, $b = -11$ mm, $\phi_i = 0.08\pi$. At the end of the injection period, the vertical orbit is rapidly dropped down by an additional 5 mm to avoid parasitic hits during the rest of the cycle.

The painting magnets are modeled using two sets of thin correctors elements (one for horizontal motion and one for vertical motion) configured as 4-bumps.

Longitudinal Painting

Because the linac and booster ring rf frequencies are not integer multiples, some injected linac bunches can fall near the ring rf bucket extremities where they would be lost. To prevent this, a fast bunch-by-bunch kicker in the linac front is used to select bunches. Two injection schemes are considered (Fig. 2). In the first, one dubbed "off-momentum" the linac provides a fixed momentum offset. In the second one, injection occurs at the ring reference momentum. In both schemes bunches are accepted only when they fall within the shaded areas. Injected particle move along the rf bucket

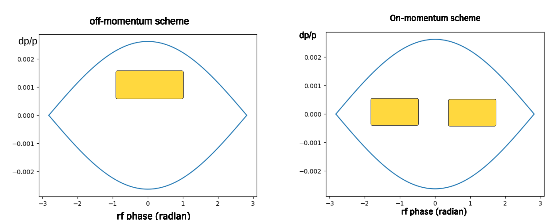

Figure 2: Left: off-momentum scheme. Right: on-momentum scheme. Linac bunches are accepted only when they fall within the shaded areas.

Hamiltonian contours and fill the phase space. Both schemes result in a depleted or empty central region. This is done so as to minimize the peak current line density which is associated with instabilities.

Foil Model

A crude estimate for large angle scattering losses may be obtained using a simple limiting aperture model. Assuming all particles origin from a point source at the foil, and a limiting horizontal aperture of transverse size x_A located at a distance s downstream from the foil, the minimum angle at the foil required for a particle to be intercepted by the aperture is $\theta_m = \frac{x_A}{\sqrt{\beta_x(0)\beta_x(s)}}$. Using $\beta(0) \sim \beta(s) = 15$ m and $x_A \sim 2.54$ cm yields $\theta_m \sim 1.6$ mrad. Assuming a similar result in the vertical plane, the probability of loss from a single large angle scattering event may be obtained by integrating the Rutherford cross section for all angles greater than θ_m and multiplying the result by the atomic surface density of the foil. For a 600μ g/cm^2 carbon foil, the probability of loss after a foil traversal is 3.5×10^{-5}. Accounting for a possible 5-10 parasitic hits during a full 0.5 ms injection, one expects an overall fractional beam loss of $\sim 10^{-4}$. Using the `PyOrbit` built-in foil element we failed observing large angle events at the expected level. As a test, we then tracked 10^7 particles with zero transverse initial angle once through the foil. While the output angular distribution matched the Gaussian core of Moliere distribution, it did not match its

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charateristic far tails. Rather than further investigating this issue, we implemented a custom foil element. Scattering is modeled as the combination of two distributions [4]: a Gaussian core of the form

$$f_c(\Theta)\,d\Omega = \frac{1}{2\pi}\exp\{-\frac{1}{2}\Theta^2\}d\Omega \tag{4}$$

and an asymptotic tail of the form

$$f_t(\Theta)\,d\Omega = \frac{1}{\pi L_c}\frac{d\Omega}{(\Theta_0^2+\Theta^2)^2} \quad . \tag{5}$$

Here Ω is the solid angle, L_c is the (dimensionless) Coulomb logarithm $\Theta = \theta/\theta_0$ is the normalized scattering angle. θ_0, the rms value of the core projected angular distribution, may be computed using a formula from Lynch and Dahl [5]. For a 600 μg/cm^2 carbon foil and 800 MeV incident protons, $\theta_0 = 2.4\times10^{-5}$ about two orders of magnitude less than θ_m. The normalized cutoff angle Θ_0 determines the point where contribution from the large angle tail becomes significant. For $\Theta >> 1$, $f_t(\Theta)$ is asymptotically equivalent to single event Rutherford scattering.

RESULTS

Figure 3 shows the beam distribution at turn 32, early in the injection. Notice that the vertical phase space ellipse is hollow because it is painted from the outside. Figure 4 shows the beam distribution at the end of the injection. The vertical phase space ellipse is now entirely filled-in.

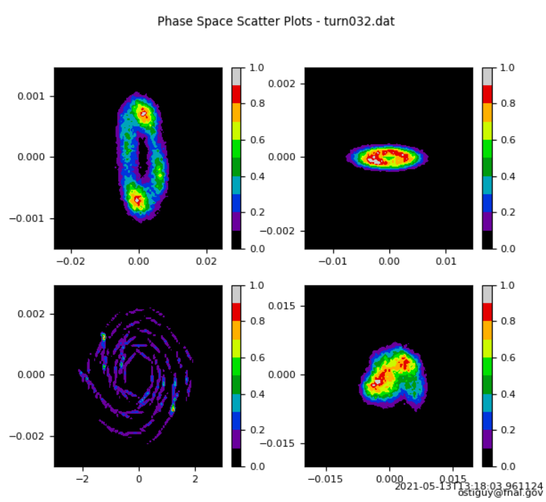

Figure 3: Beam distribution at turn 32. Top: left x-x', right y-y', Bottom: left dp/p-ϕ right x-y. Both transverse phase ellipses are now filled. The longitudinal distribution remains hollow in the center.

Figure 5 is a typical loss pattern. Perhaps unsurprisingly, most particles are intercepted by elements located immediately downstream of the foil. The inset is a map of the foil hits during injection. The average number of foil hits per particle is consistently 1.5 to 2 times larger than predicted from earlier design calculations (7 to 10). The reasons are not clear and this discrepancy remains to be explained.

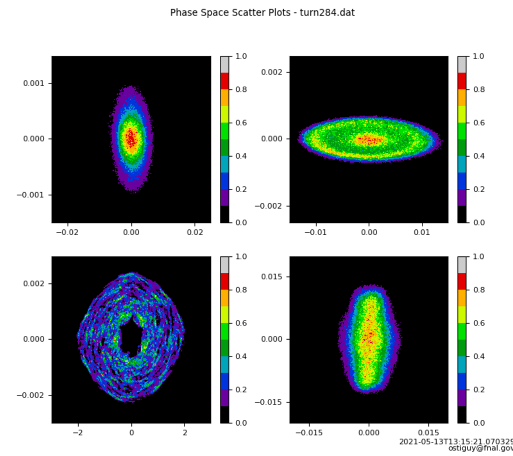

Figure 4: Beam distribution at the end of the injection. Top: left x-x', right: y-y', Bottom: left dp/p-ϕ right: x-y. Both transverse phase ellipses are now filled. The center region of the longitudinal ellipse remains hollow.

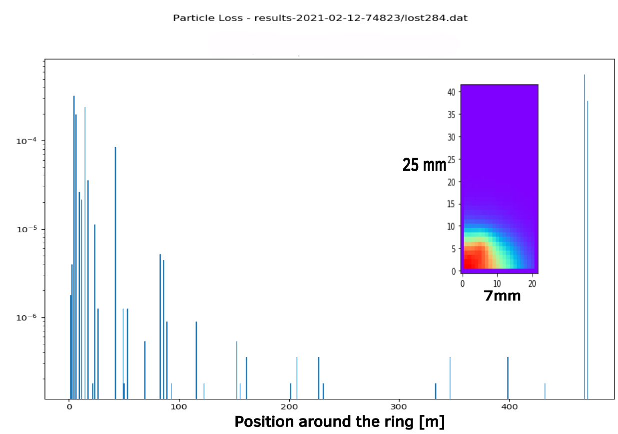

Figure 5: Large angle loss pattern. Losses around 470 m (upstream of the injection point) are likely due to a reduction in available vertical aperture at that location.

CONCLUSIONS

We used the `PyORBIT` code to simulate the entire Booster injection process, taking into account space charge and foil scattering. Early results are encouraging; however the computed losses are somewhat higher than expected. More validation testing is on-going.

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