ORBIT INJECTION DUMP SIMULATIONS OF THE H^0 AND H^- BEAMS *

J.A. Holmes, M.A. Plum, J.G. Wang, Y. Zhang, ORNL, Oak Ridge, TN, 37830, USA
M. Perkett, Denison University, Granville, OH, 43023, USA

Abstract

Simulations of the transport of H^0 and H^- beams to the Spallation Neutron Source (SNS) ring injection dump are carried out using the ORBIT code. During commissioning and early operations, beam losses in this region have been the highest in the accelerator and have presented the most obvious hurdle to cross in achieving high intensity operation. Two tracking models are employed: 1) a piecewise continuous symplectic representation of the lattice elements in the injection chicane and dump line, and 2) particle tracking in full 3D magnetic fields, as obtained from OPERA code evaluations. The physics models also include estimations of scattering from both the primary and secondary stripper foils, and beam losses due to apertures throughout the beam line.

INTRODUCTION

To reach its specified operating parameters, SNS must achieve unprecedented low uncontrolled losses of one part in 10^4. Thus far, the most severe losses are observed in the vicinity of the ring injection dump. The SNS ring injection system (Fig. 1) utilizes a stripper foil to convert a 1 GeV H^- linac beam to a circulating H^+ beam in the accumulator ring. The injection dump was designed [1] to collect H^- beam that misses the stripper foil and also incompletely stripped H^0 beam. There is an insertion in the ring, the injection chicane [2], which was designed to accommodate the merging of the injected and circulating beams and to deliver the incompletely stripped beams to the dump. The chicane consists of four dipole magnets, primary and secondary stripper foils, and four horizontal and four vertical kickers. The second stripper foil, located before the fourth chicane dipole, converts the H^- and H^0 waste beam components to H^+ for delivery to the dump, while the kickers are programmed with time-dependent waveforms to paint the circulating beam distribution. In addition to these components there is an injection septum dipole to steer the linac H^- beam upstream of the primary foil and a combined function dump septum to steer and focus the waste beams at the beginning of the dump line.

There are many constraints associated with the injection system. The primary stripper foil was placed inside the second chicane dipole in a field of 2.5 kG to magnetically strip excited H^0 states and in a field tilt $B_y/B_z > 65$ mrad to keep stripped electrons off the foil and to provide for their collection. To prevent unwanted stripping of excited H^0 states, the magnetic field in the third chicane dipole must be less than 2.4 kG. The chicane dipole fields horizontally bump the closed orbit about 100 mm, while the primary stripper foil is located horizontally about 140-150 mm outside and vertically about 46 mm above the nonbumped closed orbit. The chicane magnets must be set to close the circulating beam bump in order to minimize losses in the ring. Due to the limitations of the injection kickers, the chicane magnets must also bump the circulating beam closed orbit to within 50 mm of the primary stripper foil. In order to control the emittance of the circulating beam, the injection septum and chicane settings must be constrained to make the injected and circulating beams parallel at the primary stripper foil. A more severe constraint on the field in the third chicane bend than that provided by preventing excited H^0 stripping is due to the necessity of keeping the separation of the incompletely stripped H^- and H^0 waste beam components small to get them into and through injection dump line. Finally, the field in the fourth chicane dipole must be made as large as possible in order to bend the H^0 waste beam sufficiently to bring it into the dump septum aperture.

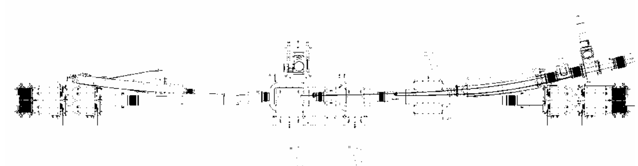

Figure 1: SNS ring injection area.

The simultaneous satisfaction of all these constraints is difficult and, indeed, was not even possible in the injection system as originally constructed. Due to unacceptable beam losses in the injection dump region, detailed experimental and computational studies of the SNS injection system were undertaken along with a program to fix the problem. The first mitigating action was to widen the second stripper foil to encompass both the H^- and H^0 waste beam components, which were further separated than was originally thought. At the same time, the chicane and septum magnet settings and the primary stripper foil position were changed from the original design values to optimize injection for the stated constraints, computational tracking studies using the ORBIT code [3] were begun using piecewise continuous symplectic models of the chicane and injection dump lines, and detailed 3D magnetic field calculations and tracking [4] using OPERA [5] were conducted for the chicane dipoles and injection dump septum.

In order to bring ORBIT's full flexibility to bear on the 3D tracking studies and to compare piecewise continuous symplectic and 3D results, a 3D field tracking module was developed and benchmarked. We now present the results of piecewise continuous symplectic and 3D tracking calculations to study issues in the SNS injection dump. We will compare the results, show how they are

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influencing decisions related to reducing the losses in the injection dump region, and demonstrate a method to tune the injection dump line.

MOVING CHICANE DIPOLE FOUR

In order to optimize the transport of the circulating beam in the ring, the fourth chicane dipole was initially placed with its horizontal center just 1 mm outside the nonbumped closed orbit. Three dimensional magnetic field calculations with the OPERA code show that, for this placement, the H^- beam bound for the injection dump passes outside the good field region of this magnet. Also, the particle tracker in OPERA indicated that the result would be to bend the H^- beam up in the vertical plane to the extent that it may suffer losses to the top of the dump septum aperture. To confirm this prediction, ORBIT calculations were carried out, both using the usual piecewise symplectic tracking and also the 3D particle tracker. In the piecewise symplectic tracking, the chicane dipoles were represented as combined function magnets with the multipole strengths provided by expanding the field integrals from the OPERA calculations. Components through eighth order (where dipoles are 0, quadrupoles are 1, etc.) were retained. Without the higher order components, no vertical motion would be imparted to the beam. The 3D ORBIT tracking used the field data provided directly from the OPERA calculations.

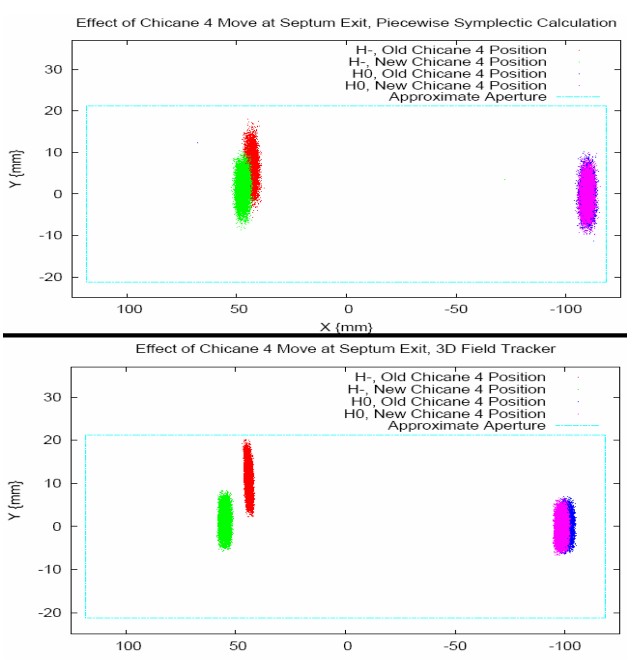

Figure 2. Piecewise sympletic (top) and 3D (bottom) beams at the exit of the injection dump septum. H^0 and H^- components are on the right and left, respectively. Red and blue correspond to original dipole four position, and green and pink to the moved dipole four. The blue rectangle shows the approximate aperture position.

Figure 2 shows the results of the ORBIT calculations. The red beam footprints both show the vertical displacement of the H^- beam component at the dump septum exit, although the displacement is somewhat greater, and dangerously close to the top, with the 3D tracker. The position of the H^0 component, too close to the right (inside) septum boundary is also apparent, especially with the symplectic tracker.

As a remedy for the vertical H^- displacement problem, it was proposed to move chicane bend four horizontally outside by 8 cm in order to bring the H^- beam into the good field region. The tracking results in Fig. 2 show the effect of such a move on the H^- and H^0 beam components. Both piecewise symplectic and 3D field tracking show that the H^- (green) beam is lowered to near the vertical midplane, while the H^0 beam is unaffected. Additionally, a piecewise symplectic simulation of the accumulation of the circulating beam in the ring has shown that the 8 cm move of chicane dipole four has little effect on this process. Based on these results, chicane dipole four has now been moved.

It is worth noting the basic, if not detailed agreement between the piecewise symplectic and 3D field tracking results shown in Fig. 2. Differences can be attributed to the number of terms retained in the multipole expansion and to the lack of full 3D information in the piecewise symplectic model. Even so, the effect of the choice of location of chicane dipole four on the H^- beam and its lack of effect on the H^0 beam are consistent between the two tracking models.

TUNING THE DUMP LINE

Originally, the ring beam dump line was designed with the combined function septum magnet to bend and focus the H^- and H^0 beams and a quadrupole magnet almost 6 m downstream to provide further focusing. Except for a couple of dipole corrector magnets, these were the only controls in the 28 m dump line. Using these magnets alone, it was not possible to simultaneously transport both the H^- and H^0 beam components to the dump. To rectify this situation, a C magnet, designed to deflect the H^- beam but not the H^0 component, was proposed to be installed following the septum. We have carried out calculations, both with piecewise symplectic and 3D tracking models of the chicane dipoles and septum, to demonstrate the use of the septum and C magnet to tune the dump. The results are similar, though not numerically identical, for the two methods, so we present the 3D results here. Because the quadrupole is used to focus the beams vertically, we use its nominal strength in these calculations.

Figure 3 demonstrates the tuning method by showing the H^- and H^0 horizontal beam centroids along the dump line, starting after the septum and ending at the dump, at different stages of the process. In the top plot, the red and blue curves show the H^- and H^0 centroids, respectively, for a nominal septum current and the C magnet turned off. Neither beam component reaches the dump, where the aperture has a radius of about 100 mm. By turning up the septum current from 2914 A to 2988 A, we can focus the H^0 beam (pink curve) on the dump. However, the H^- beam (green curve) is still lost. This is remedied by activating the C magnet with a 4 mrad kick, resulting in the red curve in the bottom plot, which shows the H^- beam reaching the dump. However, activation of the C magnet has some effect on the H^0 beam component, and we estimate that this would alter the pink curve of the top to become the bottom plot blue curve, which is no longer centered at the dump. With a final small readjustment of both the septum and the C magnet, both the H^- (green) and H^0 (pink) beams can be transported to the dump. Based on these calculations, the C magnet has now been installed in the injection dump line.

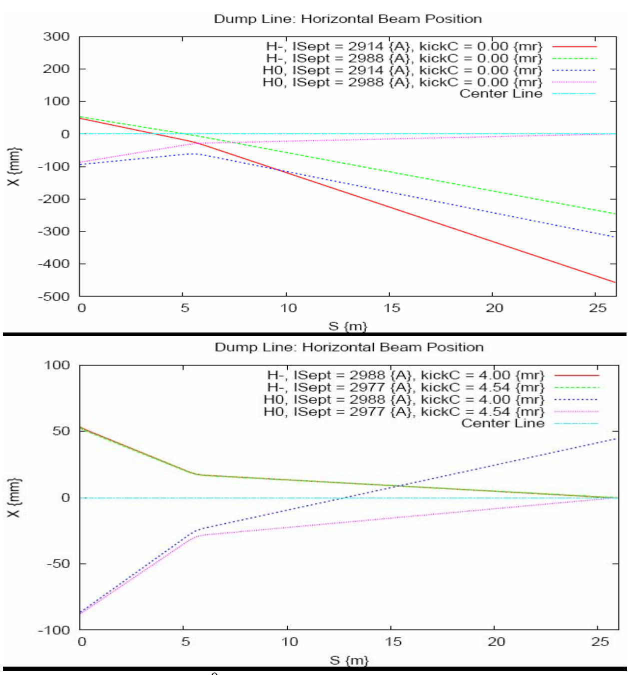

Figure 3. H^- and H^0 horizontal beam centroids during the tuning process.

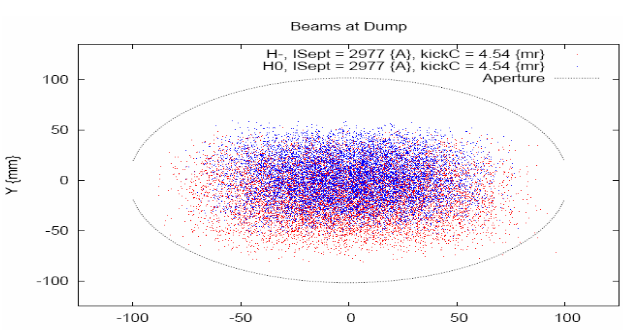

Figure 4. H^- and H^0 beam distributions at the dump.

The vertical motion of both the H^- and H^0 beams is much closer to the center, with the H^- centroid position about 14 mm below the center and the H^0 centroid about 2 mm above center at the dump. This would not be the case if chicane dipole four were in its original position. Figure 4 shows the beam distributions at the dump for the final tuned case. There is essentially no beam loss other than that induced by large angle scattering in the primary and secondary foils.

SEPTUM APERTURE SIZE

In order to ensure reduced beam losses in the injection septum, an increase in the aperture size by about 2 cm (30%) in the vertical direction is under consideration. This opening of the septum changes the details of its bending and focusing actions. Although 3D modeling of this effect is yet to be carried out, we have carried out piecewise symplectic calculations based on integrated field estimates from a 2D magnet calculation. The result is that the beam separation increases from 15.3 cm to 17.0 cm at the septum exit. Such an increase could lead to increased beam losses at the left and right septum sides, but the study is just beginning.

BEAM LOSSES

The injection dump line simulations carried out thus far have employed a Gaussian distribution of RMS emittance 0.28 mm-mrad and truncated at 8 sigma. Neglecting losses due to large angle foil scattering, no loss is predicted for the tuned dump case. The calculations suggest that the likeliest cause of losses in real beams is due to the scraping of the H^0 component against the right hand side of the dump septum magnet and, for that reason, it is necessary to set the chicane dipoles to push the incompletely stripped beams as far left as possible.

Finally, for the cases in which both the H^0 and H^- beams were transported to the IDUMP and the calculated beam losses were zero, we calculated the losses due to scattering from the secondary foil, modeled as 25 mg/cm^2 of carbon, and alternatively from the secondary foil view screen, modeled as 389 mg/cm^2 of aluminum oxide. The orbit foil model includes small angle multiple Coulomb scattering, Rutherford scattering, and elastic and inelastic nuclear scattering. We found that scattering losses from the secondary foil view screen exceeded those from the secondary foil by a factor of 19±3. The experimentally observed ratio is 17. These losses were due to large angle nuclear or Rutherford scattering processes. Losses from the secondary foil and from the view screen averaged about 0.044% and 0.85%, respectively.

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