1 H^- INJECTION AT 8 GeV

The charge-exchange stripping method of Budker and Dimov[i] is used to inject the H^- beams of the 8 GeV Linac into the Main Injector. The beam layout is similar to those of the JHF 3 GeV synchrotron[ii], the SNS[iii], and the Fermilab Booster[iv].

Challenging features of the 8 GeV injection include the maximum B field of 600 Gauss (bend radius $\rho = 500$ m) needed to avoid stripping the 8 GeV H^- ions, and the small spot size on the injection foil ($\sigma = 1\sim2$ mm). Favorable aspects include the 15 m free space between quadrupoles in the MI straight section, and the low 0.67 Hz repetition rate compared to the 60 Hz SNS rate.

1.1 Example Injection Layout

A representative injection layout (Figure 1), transverse painting scenario, and loss simulation was developed by A. Drozhdin for this design study[v].

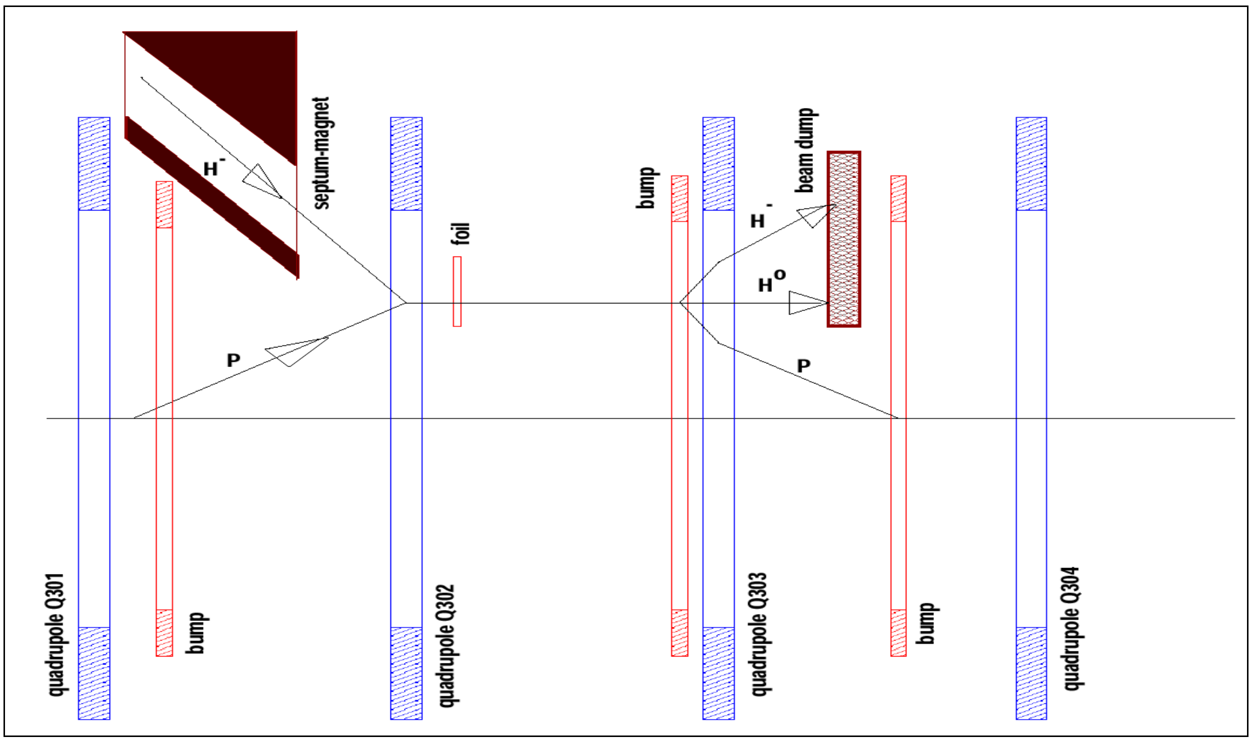

Figure 1 - H^- Injection layout in the MI-30 straight section. A horizontally bending septum magnet brings the incoming H^- beam within 23 mm and 2 mr of the nominal beam trajectory as it reaches focusing quadrupole Q302. Simultaneously the proton beam orbit is bumped outwards 23 mm by a set of three pulsed "bump" dipoles. The two beams are merged in a 300 gauss dipole field as they pass through Q302 off center. Downstream of Q302 a pair of 1-micron stripping foils converts 99.6% of the H^- to protons[vi]. The remaining H^o and H^- ions are separated from the circulating proton beam by downstream magnets and sent to a beam dump. Horizontal phase space painting is accomplished by collapsing the bump in the closed orbit as injection proceeds. Vertical phase space painting is accomplished with vertical bump magnets (not shown) in the H^- injection line to produce a vertical angle bump at the foil. The vertical angle decreases from an initial maximum value to zero as the bump proceeds, producing an "uncorrelated" painting

pattern[ii] that avoids injecting particles that have the maximum betatron amplitude in both coordinates.

1.2 Phase Space Painting

The stripping foil geometry is shown in Figure 2.

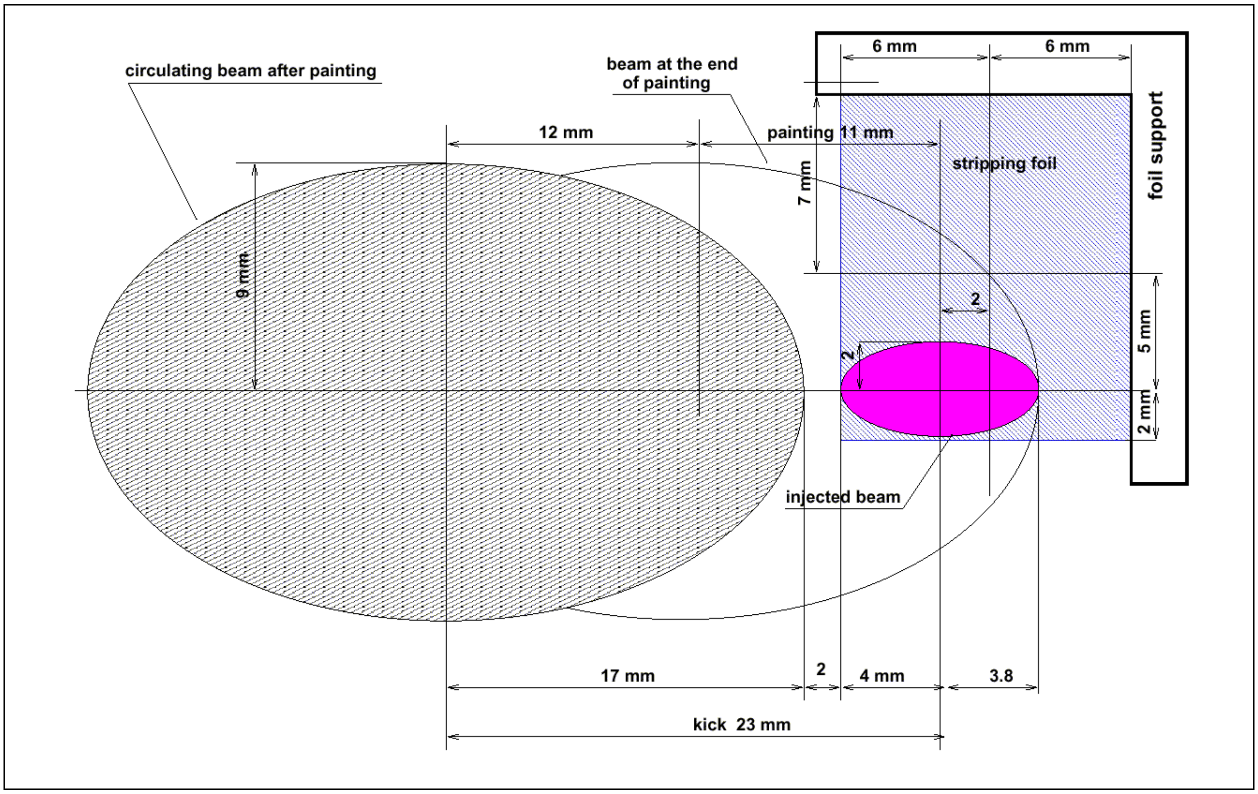

Figure 2: H^- stripping foil geometry for the 8 GeV Linac. The 12 mm x 14 mm foil is supported on two edges. At the start of injection painting the circulating beam orbit is bumped horizontally outwards by 23 mm. The amplitude is gradually decreased as painting proceeds. The injected H^- beam envelope (pink) stays fixed on the foil. A separate set of vertical bump magnets in the injection line (not shown) control the vertical angle on the foil. The vertical angle is initially a maximum and is gradually decreased to zero as painting proceeds. The circulating beam envelopes at the end of injection, and after the circulating beam is removed from the foil, are also shown.

1.3 Optimum Painting Waveforms

The optimal injection painting waveforms[vii] to produce an "uncorrelated" beam for 90-turn (1 msec) injection are:

- In the horizontal (orbit bump) plane, the bend field B vs. turn number N is given by:

$$B = Bo\left[0.5217 + 0.4783\left(1 - \sqrt{\frac{2N}{90} - \left(\frac{N}{90}\right)^2}\right)\right] \qquad \textit{for} \quad N < 90$$

$$B = Bo\left[0.5217 - \left(\frac{N-90}{3.83}\right)\right] \qquad for \quad N > 90$$

and in the vertical (injection angle bump) plane, the vertical slope at the foil is:

$$Y' = 0.6789\ mrad\left(1 - \sqrt{\frac{2N}{90} - \left(\frac{N}{90}\right)^2}\right)$$

1.4 Stripping Foil Heating and Lifetime

A simulation of various injection scenarios was performed[v]. For the baseline (90-turn) injection with standard emittances and 150 um carbon foil), each proton passes through the foil once as an H^- ion and an average of 6.3 times as a stripped proton. The dE/dx for the H^- is three times larger than for the circulating protons. The foil heating is dominated by the hot spot where the H^- beam ($\sigma \sim 1$ mm) stays parked at one spot on the foil. An ANSYS simulation[v] indicated an adiabatic temperature rise of 2400°C for a single shot through the foil. This is probably acceptable if the H^- injections are separated by 1.5 seconds. If the MI injections occur at 10 Hz (for example in some sort of 8 GeV stretcher-ring scenario), a peak temperature of 3500°C is reached, which is near the temperature required for prompt failure of carbon foils[viii]. Thus the stretcher-ring scenario will probably require either successful R&D on diamond foils[ix], or some sort of rotating spindle to ensure that no single spot of foil keeps getting hit at 10 Hz.

It is clear that there is not a lot of margin on the stripping foil survival in the simplest scenarios, and is therefore included on the R&D list (Appendix 3). It is not likely a show-stopping issue because of the backup of a spindle-based solution for foil lifetime.

1.5 Main Injector Beam Loss Calculation from Foil Scattering and Interactions.

The simulation of H^- injection losses[v] included foil nuclear interactions, multiple scattering, the proposed injection and painting geometry and the focusing lattice and aperture restrictions in the Main Injector. The loss pattern in the Main Injector is shown in Figure 3. The fraction of beam loss from nuclear interactions in the foil was 2×10^{-5} and the overall fractional loss from the combination of painting and multiple scattering in the foil was 2.5×10^{-4}. This simulation does not include losses from RF capture, space charge, or other loss mechanisms which will probably be dominant.

1.6 H^o Excited States and Delayed Stripping

The excited Rydberg states of neutral hydrogen are significant source of beam losses downstream of the stripping foil[ii]. These losses depend on foil thickness and can be comparable to downstream losses due to nuclear scattering in the foil. These excited states are quickly stripped in magnetic fields exceeding a critical value, which depends on the principal quantum number N. Downstream losses result when these are magnetically stripped partway through the bend magnets that complete the proton orbit bump.

The 10 m unoccupied drift downstream of the stripping foil offers two convenient ways of dealing with this problem:

1) A subset of the Rydberg states can be deliberately stripped by placing a dipole magnet of judiciously chosen strength downstream of the foil[x]. At 8 GeV, a value of 410 Gauss will strip states with $N \geq 5$ while leaving $N < 5$ largely untouched[x]. A short pair of opposed DC dipole magnets will ensure that stripped states will fall largely inside the ring acceptance, while the unstripped states will hit the neutral beam dump.

2) An alternative solution is to add a second thin stripping foil ~10 cm downstream of the first. Since the fraction of the beam that emerges in excited neutral states depends exponentially on foil thickness, beam losses from delayed stripping can be brought to negligible levels. This second foil may be significantly thicker than the first because the 3x higher dE/dx of the H^- beam is not present in the second foil. The thickness of the first foil can be reduced in this scenario, which eases the foil heating due to improved cooling from a larger surface/volume ratio.

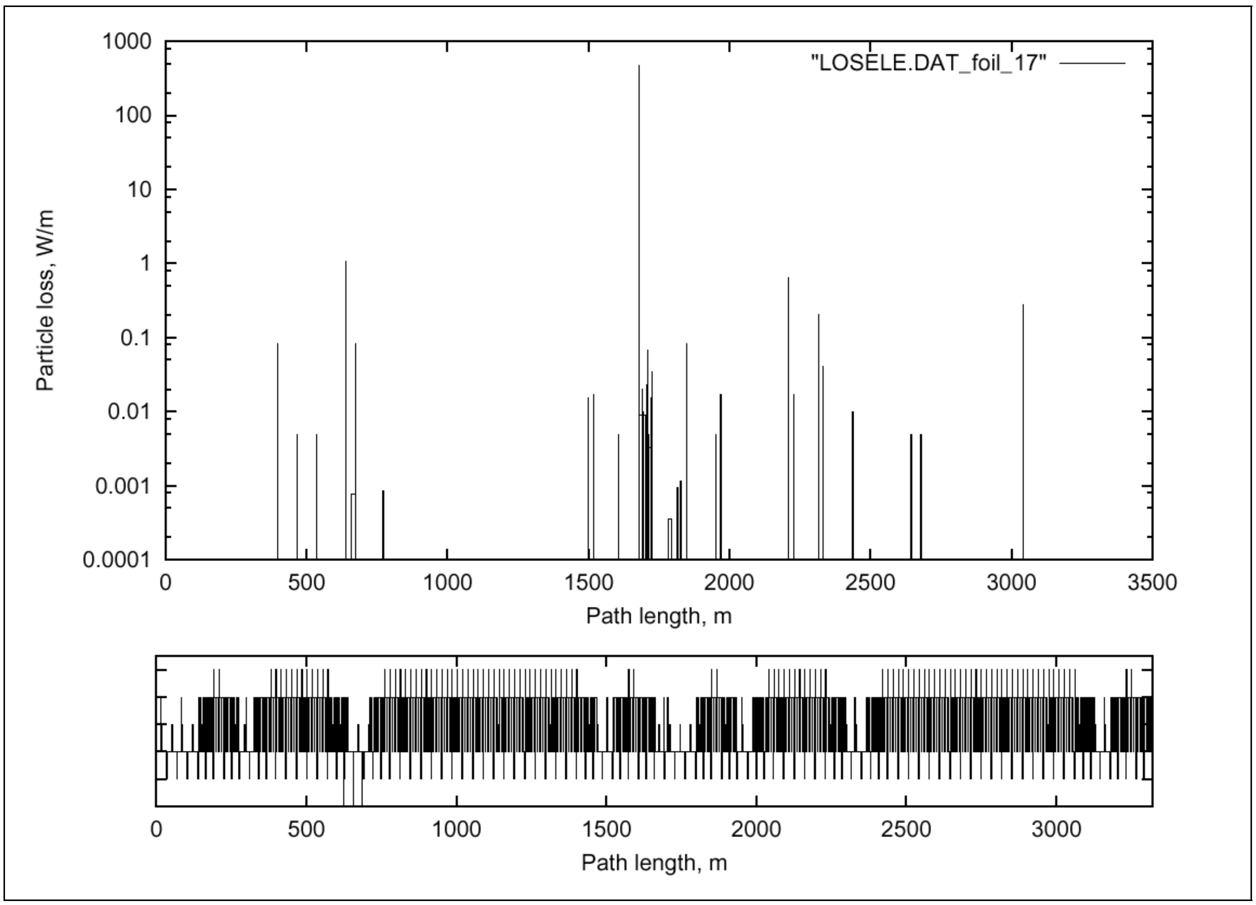

Figure 3 - Injection Beam loss distribution in the Main Injector with graphite foil thickness of 1.5 um and 90-turn injection of painted beam with nominal emittance. The fraction of beam loss from nuclear interactions in the foil was 2×10^{-5} and the overall rate of losses from the combination of painting and multiple scattering in the foil was 2.5×10^{-4}. This simulation does not include losses from RF capture, space charge induced halo, or other loss mechanisms that will probably be dominant.

[i] G. I. Budker and G. I. Dimov, "On the Charge Exchange Injection of Protons into Ring Accelerators", The International Accelerator Conference, Dubna 1963, CONF-114, USAEC TID-4504, pp. 1372-1377

[ii] H - PAINTING INJECTION FOR THE JHF 3-GEV SYNCHROTRON, Y. Irie et al., EPAC98 http://accelconf.web.cern.ch/AccelConf/e98/PAPERS/MOP23C.PDF

[iii] SNS/BNL Note#3, "H- Charge Exchange Injection into the 1 GeV NSNS Accumulator", Blumberg, Y.Y.Lee http://server.c-ad.bnl.gov/esfd/bnlsns/03.pdf

[iv] "THE MULTITURN CHARGE EXCHANGE INJECTION SYSTEM FOR THE FERMILAB BOOSTER ACCELERATOR, C. Hojvat et al., FNAL-TM-872 (1979) http://library.fnal.gov/archive/test-tm/0000/fermilab-tm-0872.pdf

[v] A. I. Drozhdin and G. W. Foster, "Painting Injection into the Fermilab Main Injector", Oct 21, 2003. http://www-ap.fnal.gov/~drozhdin/prdriver/pap.pdf

[vi] H- Stripping efficiency vs. foil thickness was estimated by neglecting any energy dependence.

[vii] "JHF Accelerator Design Study Report", KEK Report 97-16, JHF-97-10, March 1998, p3-67ff the most recent version of the JHF TDR is online at: http://hadron.kek.jp/member/onishi/tdr2003/

[viii] Lifetime of Carbon Stripping Foils for the Spallation Neutron Source", C.J. Liaw et al., PAC2001 http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/TPAH138.PDF

[ix] THIN DIAMOND FILMS FOR SNS H- INJECTION STRIPPING, R. W. Shaw et al, PAC03 http://accelconf.web.cern.ch/accelconf/p03/PAPERS/ROPB004.PDF

[x] Grahame Rees, pvt. comm.