H^- INJECTION STUDIES FOR THE FERMILAB PROTON DRIVER

C.R. Prior*, CLRC, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, U.K.

Abstract

Details are given of a study of the H^- injection scheme proposed for the Fermilab Proton Driver, with particular reference to its possible use as part of a neutrino factory. Both longitudinal and transverse aspects have been covered. In the longitudinal plane, a continuous sequence of parameters has been found that generates the longitudinal emittance required by the design, with very low particle loss. Transversely, repeated computer simulations of non-linear space charge effects have led to re-assessment of the tunes and method of phase space painting. The paper describes the codes used in the modelling and the general approach taken to optimise the overall scheme.

1 INTRODUCTION

A rapid cycling synchrotron, described in a design report published in December 2000 [1], has been proposed as a replacement for the Fermilab Booster. Such a machine would provide an upgrade path for NuMI and other fixed target projects. In the medium term, it could serve as the driver for a neutrino factory and, at a later date, it could be upgraded to a 4 MW proton source for a muon collider. The development of the Proton Driver is likely to take two phases. Phase I would provide 1 MW of beam power at 12 GeV with a 53 MHz rf system (matching the existing main injector). Phase II, taking the beam to 16 GeV with a new 7.5 MHz rf system, has the goal of generating sufficient muons for neutrino factory studies. In both cases, the H^- injection schemes are designed for very low losses, which are confined to a small area of the ring, allowing hands-on maintenance elsewhere. A flexible momentum compaction (FMC) lattice (see Fig. 1) has been adopted, and injection painting has been employed to reduce space charge effects. This paper concentrates on Phase II for which the main parameters for injection studies are given in Table 1.

2 LONGITUDINAL INJECTION

Injection of the H^- ions is via a carbon stripping foil, of 300 μg/cm^2 thickness, supported on two sides with two free edges. A total of 3×10^{13} particles are to be injected over 27 turns at harmonic number $h = 18$. To help minimise injection losses, the incoming linac beam is chopped with a 70% duty cycle at the ring bunch repetition frequency. The magnetic guide field for the injection, acceleration and trapping process is a superposition of two frequencies designed to approximate closely to a linear rise:

$$B(t) = B_0 - B_1 \cos 2\pi f t + \frac{1}{8} B_1 \sin 4\pi f t,$$

where $f = 15$ Hz, $B_0 = 0.79$ T and $B_1 = 0.69$ T. Cavity voltages are carefully controlled to ensure that all particles are trapped in the stable phase space buckets. Optimum parameters have been found using the RAL code TRACK1D, which in interactive mode allows continuous updating of values until a suitable scheme is achieved. The resulting total peak cavity voltage is in agreement with independent

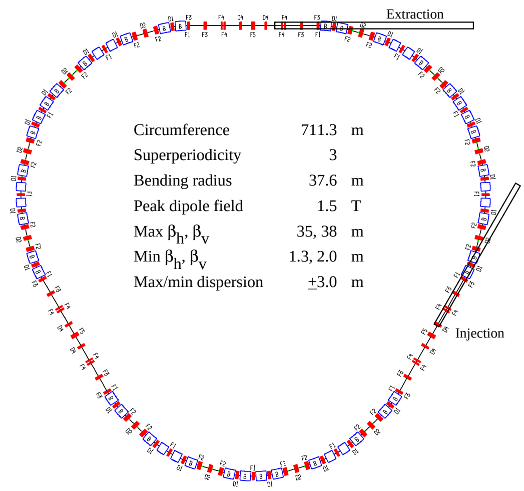


Figure 1: Fermilab Proton Driver FMC Lattice

Table 1: Injection parameters for the Fermilab Proton Driver Phase II.

Injection energy	400 MeV
Number of particles	3×10^{13}
Number of injection turns	27
Ring β-functions at foil	22.89 : 9.23
Transition γ	27.71j
Linac emittance (full, unnormalised)	4.42 π μrad.m
Ring emittance (full, unnormalised)	59.0 π μrad.m
$Q_h : Q_v$	12.43 : 11.38
Peak rf voltages	1.45 MV
Harmonic number	18
Ring circumference	711.3 m
Injection period	90 μs

* Work carried out while the author was a guest at the Fermi National Accelerator Laboratory, Batavia, Illinois, August-September 2000.

work carried out at the Fermi Laboratory [1] and is depicted in Fig. 2. Simulation of the injection stage of the

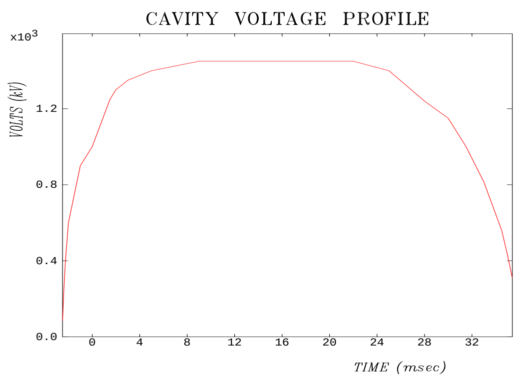


Figure 2: Cavity voltage profile for Proton Driver Phase II.

synchrotron cycle for longitudinal phase space in Phase II is summarised in Fig. 3.

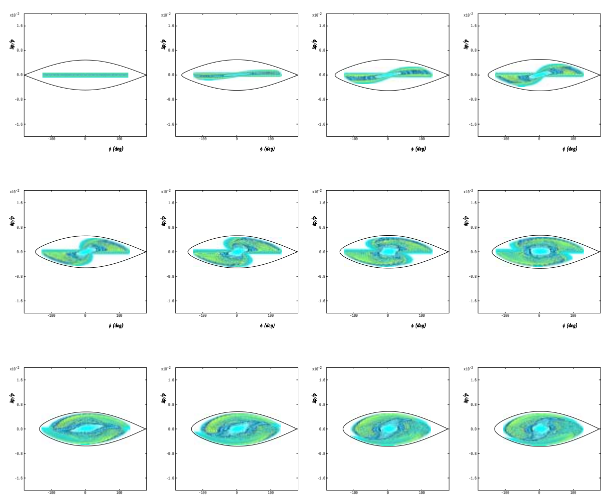


Figure 3: Longitudinal injection for Phase II.

There is no beam loss predicted in this scheme, apart from that due to H$^-$ and proton interactions with the foil, which are expected to be of the order of 10^{-3}. Provided the containing voltages from the rf cavities are sufficient, acceleration and trapping appear straightforward, and the design goal of a longitudinal emittance of 0.4 eV.s can be achieved. On the other hand, a low loss scenario for Phase I is somewhat harder to achieve within the voltage constraints of the agreed proposals. Current modelling estimates suggest that the order of 20% of the beam will fail to be trapped successfully.

3 TRANSVERSE INJECTION

In the transverse plane, the design report [1] envisages a matched injection scheme with an elliptic horizontal orbit bump variation, known (for infinitely many turns and in the absence of space charge) to lead to a uniform transverse beam distribution. However, for H$^-$ injection schemes in high intensity machines, consideration also needs to be given to space charge effects and to protecting the stripping foil against high temperatures by minimising the number of subsequent traversals by re-circulating protons. Mismatched injection schemes generally give more flexibility for injection painting, and careful variation of the closed orbit bumps during injection is essential for controlling foil heating.

The Fermilab injection scheme uses programmed orbit bumps in the horizontal plane and variation of the angle of the incoming beam in the vertical plane. Simulations have been carried out using the RAL code TRACK2D, which contains a finite element Poisson solver for calculating nonlinear space charge. The effects of image charges in an elliptical vacuum chamber ($5'' \times 9''$) were included and a total of 200,000 particles were tracked. Initial simulations of an early model of the lattice showed a pronounced fourth-order space charge resonance and large emittance increase. Re-optimising to the split tunes in Table 1 has eliminated this effect. With an analytical closed orbit programme for $N = 27$ injection turns given by

$$x_n = \begin{cases} x_N + (x_0 - x_N)\left(1 - \sqrt{\frac{n}{N}\left(2 - \frac{n}{N}\right)}\right) & n \leq N \\ x_N\left[1 - \frac{1}{6}(n - N)\right] & N < n \leq N + 6 \end{cases}$$

where $x_0 = 49.8$ mm and $x_N = 24.0$ mm, and an incoming beam angle during injection given by

$$y'_n = y'_0\sqrt{1 - \frac{n^2}{N^2}} \qquad (y'_0 = 1.84\,\text{mrad})$$

the simulations show a 95% beam emittance after 34 revolutions of $\epsilon_h = 69.5\,\pi\,\mu$rad.m (12.2 rms), $\epsilon_v = 82.6\,\pi\,\mu$rad.m (12.4 rms). However, it has proved possible, by selecting orbit and angle variation to take into account both space charge and the need to reduce proton foil traversals, to lower these figures to $\epsilon_h = 52\,\pi\,\mu$rad.m (10.0 rms) and $\epsilon_v = 62.5\,\pi\,\mu$rad.m (8.9 rms). In the latter case, the emittance in the horizontal plane, smaller than

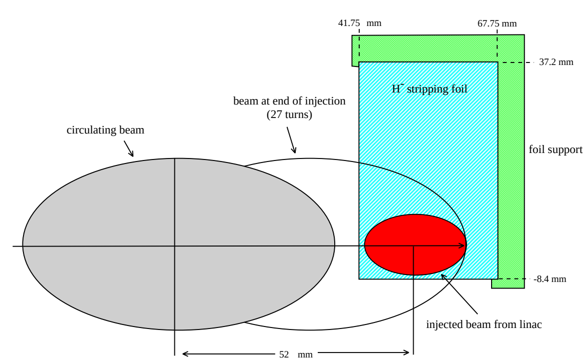
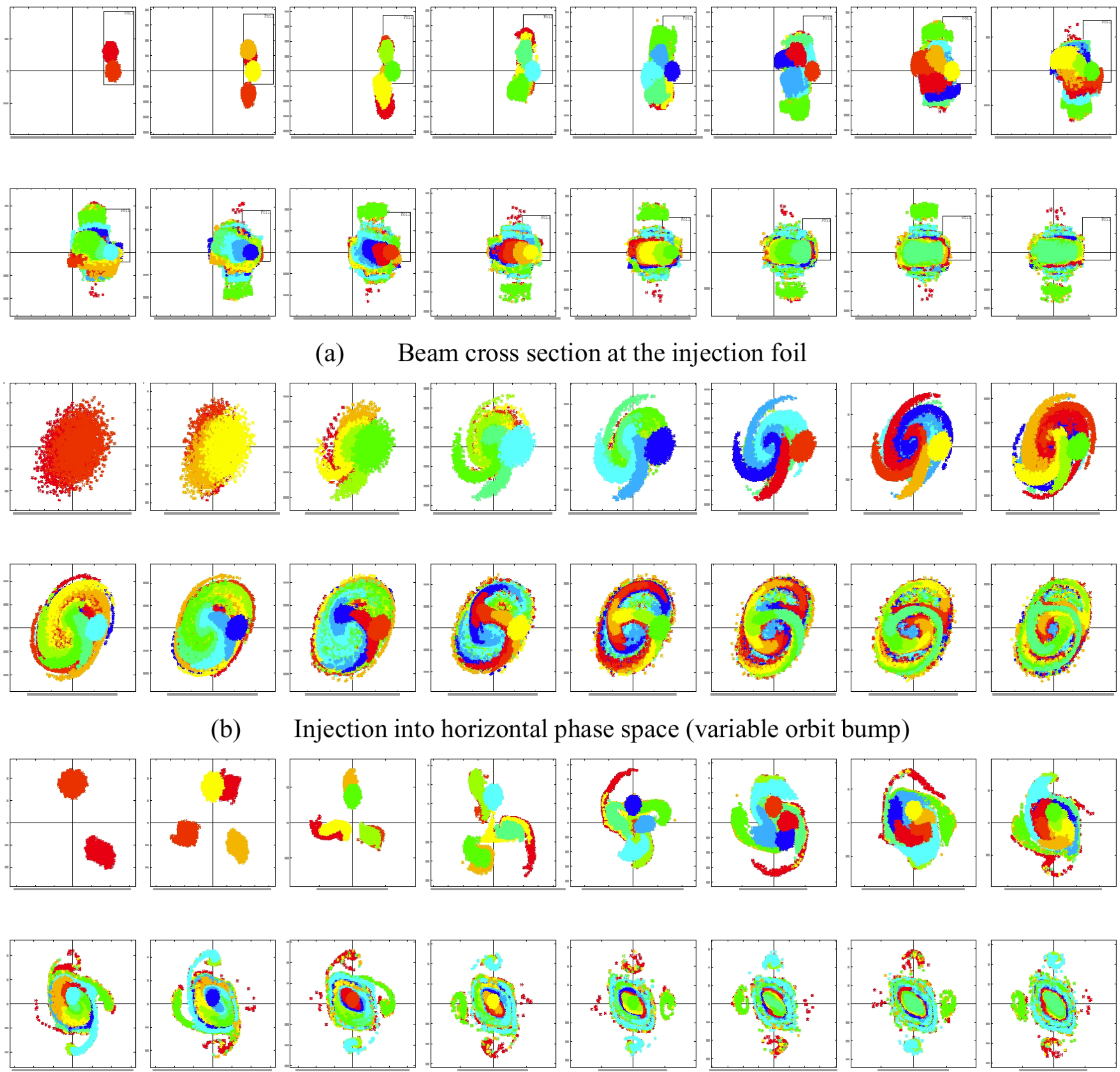


Figure 4: Details of injection process at the foil.



(a) Beam cross section at the injection foil

(b) Injection into horizontal phase space (variable orbit bump)

(c) Injection into vertical phase space (variable injection angle)

Figure 5: Transverse injection for Phase II.

the design specification, is a consequence of space charge wrapping the turns around the distribution in phase space. The larger ratio of full:rms emittances in the vertical plane indicates a concentrated core with a diffuse halo, which could probably be improved with further optimisation of the painting parameters. On average, each circulating proton particle intersects the foil 2.6 times, and the corresponding peak foil temperature should not exceed $600\,^{o}$K. A schematic view of the injection process is shown in Fig. 4 and details of the final simulation are shown in Fig. 5. Plots of beam cross section, and horizontal and vertical phase space are shown on every fourth revolution of the machine.

Some further optimisation seems possible. For example, the RAL code FOILHITS, developed in connection with the ESS [2] and UK Neutrino Factory [3] studies, is able to generate improved orbit bump schemes to minimise foil traversals for a range of injection scenarios. The final beam distribution may be taken into account as required. Mismatched injection studies are due to be undertaken and a new ring lattice with a smaller radius is being explored. Momentum effects and coupling between the longitudinal and transverse planes also need to be investigated.

4 REFERENCES

[1] W. Chou, C. Ankenbrandt and E. Malamud (eds), "The Proton Driver Design Study," Fermilab-TM-2136, December 2000.

[2] G. Bauer, T. Broome, D. Filges, H. Jones, H. Lengeler, A. Letchford, G. Rees, H. Stechemesser, G. Thomas (eds), "ESS: A Next Generation Neutron Source for Europe. Vol III: The ESS Technical Study". November 1996.

[3] C.R. Prior and G.H. Rees, "Synchrotron-based Proton Drivers for a Neutrino Factory," Proceedings of the 7th European Particle Accelerator Conference, EPAC'00, Vienna, Austria, June 2000.