

INJECTION DYNAMICS AND MULTITURN CHARGE-EXCHANGE INJECTION INTO THE FAST CYCLING SYNCHROTRON FOR THE SNS

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Summary

The Spallation Neutron Source (SNS) under construction at the Rutherford Laboratory is based on a high intensity, 800 MeV proton synchrotron, cycling at 50 Hz. An injected proton intensity of  $5 \times 10^{13}$  protons/pulse is obtained by injecting approximately 250 turns of negative hydrogen ions through a stripping foil in a charge-exchange injection system. The injection system is described and the results of studies on the injection dynamics are presented. The multiturn phase space stacking of the beam and the resulting proton density distributions have been studied with an aim to minimising beam instability problems in the synchrotron. With multiple traversals of the stripping foil, it is shown that obtaining high stripping efficiency with minimum scattering in energy and angle, places a severe constraint on the foil thickness in a high intensity machine. The high mean foil temperature and the thermal cycling produced by the high mean and pulsed current require the foil to be of a refractory material and the results of investigations into suitable materials are presented.

Introduction

A negative-ion injection system has been designed for injecting protons into the synchrotron of the SNS. Although such systems are operating successfully at ANL and FNAL, the one for the SNS is to operate at considerably higher pulsed and mean intensities.<sup>1,2</sup> At full intensity,  $5 \times 10^{13}$  protons are injected per pulse and with the synchrotron cycling at 50 Hz this gives a mean intensity at injection of  $2.5 \times 10^{13}$  protons/sec,

Negative-ion Injection into the SNS Synchrotron

Negative hydrogen ions are injected into the synchrotron at an energy of 70 MeV and are stripped of electrons by a stripping foil in the synchrotron.

The synchrotron acceptance is brought onto the foil during the injection process by magnetically deflecting the central equilibrium orbit. The deflection is removed at the end of injection to minimise the number of foil traversals by the circulating proton beam during acceleration.

The layout of the injection straight-section is shown in Figure 1. The closed orbit deflection is produced by four pulsed injection dipole magnets. The stripping foil is situated between the central pair of dipoles at the symmetry point of the "beam bump". Negative hydrogen ions are injected on the inside radius of the synchrotron and a dc septum magnet deflects the ions into the aperture of the 2nd injection dipole and onto the foil.

The four injection dipole magnets are identical in construction and are powered in series to give a symmetrical 'beam bump' within the straight section. The dipoles are in vacuum and are single turn septum magnets with ferrite yokes. The current feeds at the back of the yoke are water cooled but the coils cool by conduction to the current feed points. The dc septum magnet is positioned alongside the first

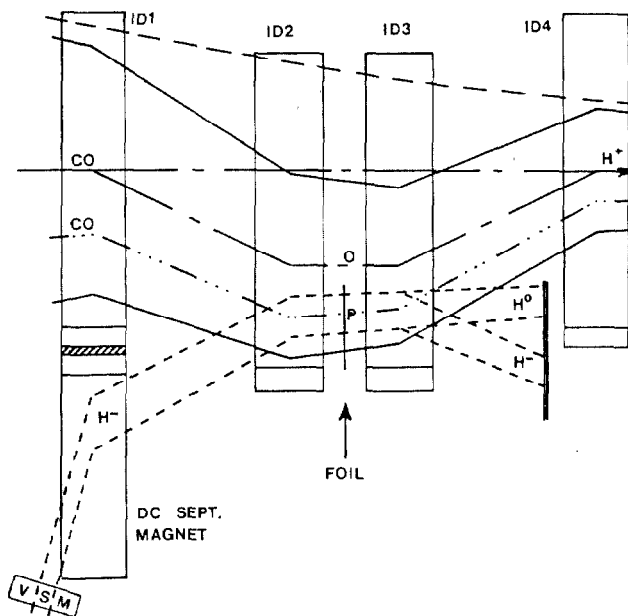


Fig 1: Layout of SNS Injection System.

injection dipole with its septum facing that of the dipole. It is separated by the dipole vacuum chamber and a magnetic shield, to shield the dc septum magnet fringe field from the circulating beam. The vacuum chamber also provides an effective buttress for the multiturn dc septum.

The synchrotron radial and vertical acceptances are 540 mm mrad and 430 mm mrad respectively. The negative-ion beam from the linac is collimated to an emittance of 25 mm mrad. The momentum spread,  $\delta p/p$ , of the injected ions is  $1.2 \times 10^{-3}$ .

The synchrotron has a hybrid combined function/separated function magnet lattice.<sup>3</sup> The combined function dipoles are excited by a dc biased, 50 Hz ac current. The H<sup>-</sup> ions are injected as the ac guide field is decreasing to its minimum value and ceases 100  $\mu$ sec before the minimum to allow time for adiabatic rf trapping and high trapping efficiency.

At the start of injection, the momentum corresponding to the central equilibrium orbit is higher than that of the injected hydrogen ions. The maximum relative momentum difference,  $\Delta p/p$ , of the H<sup>-</sup> ions is chosen to be  $-16.5 \times 10^{-3}$ , which corresponds to starting injection 476  $\mu$ sec before the guide field minimum. This maximum value of relative momentum "error" is determined primarily by practical constraints on the range of the programmeable "TRIM" quadrupole power supplies used to correct the tune during injection.

The normalised radial phase space acceptance at the start of injection is shown in Figure 2. The momentum "error" closed orbit for the injected ions starts at  $P \{ (\alpha_p/\sqrt{\beta}) (\Delta p/p), (\alpha_p/\sqrt{\beta} + \alpha_p' \sqrt{\beta}) (\Delta p/p) \}$  relative to 0 and moves from P to 0 as the guide field decreases to the minimum. With  $\Delta p/p = -16.5 \times 10^{-3}$  and injecting at point P, the injected beam is contained well within the acceptance. However, some acceptance is required to contain the emittance

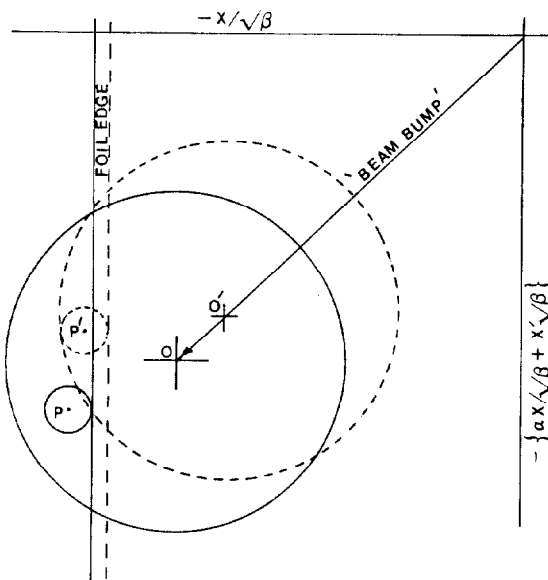


Fig 2: Normalized Radial-Space Acceptance.

growth produced by the stripping foil and the acceptance may be filled by a) injecting with an initial closed orbit error or b) injecting initially at P and partially reducing the "beam bump" during the injection interval. With the latter method, the injection point moves from P to P' and the closed orbit from P to O'. With either method it is primarily the rate of change of the synchrotron guide field which determines the stacking of the beam within the synchrotron acceptance.

With a revolution time of 1.48  $\mu\text{sec}$ , injection is from 476  $\mu\text{sec}$  to 100  $\mu\text{sec}$  before field minimum and limits the number of turns to about 250.

Stacking in the vertical phase-space is achieved by steering the injected  $\text{H}^-$  ions vertically during the injection interval using a small magnet, VSM, just upstream of the dc septum magnet. At the start of injection, particles are injected with large amplitude vertical and small amplitude radial betatron oscillations. Since early particles initially have a large momentum error, full vertical aperture must be provided to the inner radius.

#### Angular and Momentum Scattering

Negative ion injection increases beam brightness, but this relies on a conflux at the foil of the  $\text{H}^-$  ions and the circulating protons which must pass through the foil many times. Liouville's theorem is not violated because the process is non-conservative, but these effects combine to give angular and momentum scattering, which is minimised by using foils of low Z material.

Emittance growth, resulting from angular scattering, has been shown to be proportional to the average number of foil traversals.<sup>4</sup> Figure 3 shows the results of injecting 250 turns into the SNS for the two schemes a) and b) outlined above, assuming the beam bump is removed cosinusoidally in 100  $\mu\text{sec}$ .

Radially, early injected turns are stacked near the centre of the acceptance but vertically the early turns are stacked around the periphery. For scheme a) the aperture to contain the growth in injected emittance is 1 mm radially and 3.5 mm vertically.

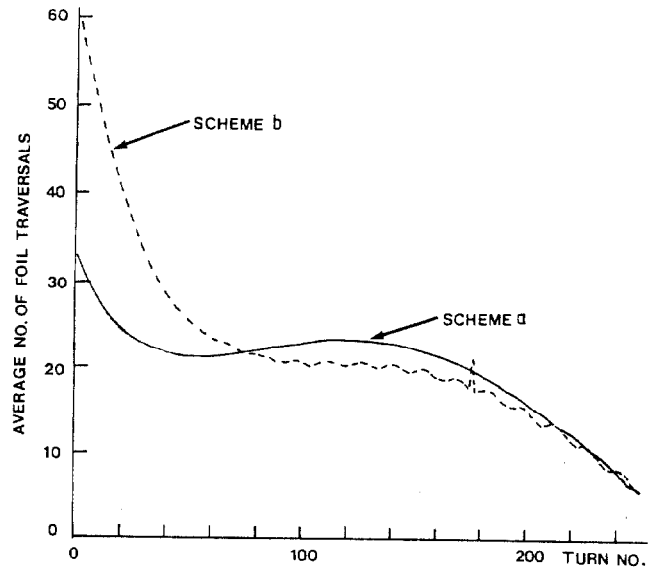


Fig 3: Average Number of Foil Traversals.

The traversal of a very thin foil by a monoenergetic beam results in a Landau energy distribution.<sup>5</sup> The mean energy loss and width of the distribution are proportional to foil density per unit area. In Figure 4 the average numbers of foil traversals are analysed to show the beam fractions which traverse the foil a given number of times.

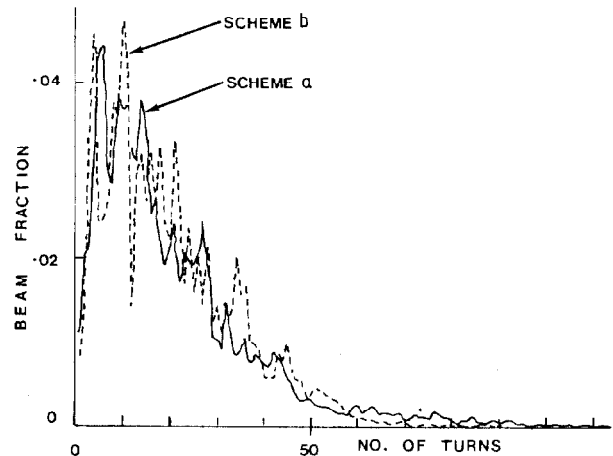


Fig 4: Fraction of Beam v. Foil Traversals.

The final energy distributions are obtained by convoluting the Landau distribution for each fraction with assumed input energy distributions and summing. The beam loss into the tails of the Landau distributions coupled with the stripping efficiency results in an optimum foil thickness as shown in Figure 5.

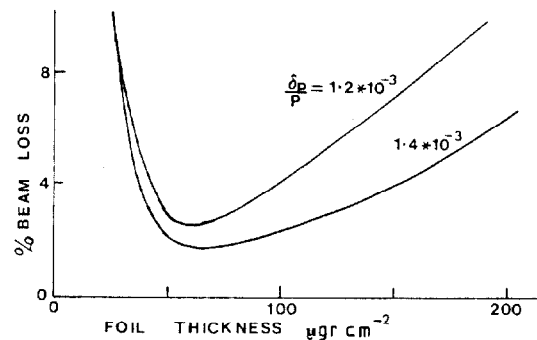


Fig 5: Beam Loss v. Foil Thickness.

### Foil Parameters

A foil 120 mm x 30 mm is required with one 120 mm edge unsupported. A thickness approximately  $50 \mu\text{gr cm}^{-2}$  gives a stripping efficiency of 98%.<sup>6,7</sup> The energy loss due to multiple traversals of the protons produces a temperature rise, in a material such as carbon, of  $260^\circ\text{C}$  during injection, cooling to  $160^\circ\text{C}$  between pulses. Since the foil is situated in the fringe fields of the inner pair of injection dipoles the stripped electrons may circulate through the foil losing their total energy and raising the temperature to  $700^\circ\text{C}$  and cooling to  $240^\circ\text{C}$ . To keep the foil temperature down studies are in hand to optimise the foil in the fringe field to collect the electrons. Increasing the thickness beyond the  $50 \mu\text{gr cm}^{-2}$  results in increased energy loss in the foil and beam loss due to energy scatter.

At full intensity, a mean current of  $50 \mu\text{A}$  of secondary electrons is emitted from the foil. To avoid electrostatic stress, insulating foils will need to be coated with a low resistivity material.

### Foil Material

The experience of work at FNAL indicated that though it is possible to obtain large area  $50 \mu\text{gr cm}^{-2}$  carbon films evaporated onto glass substrates, it would not be feasible to separate and mount such films with the necessary long unsupported edge.<sup>8</sup>

The Fulmer Research Institute (UK) studied the manufacture of  $50 \mu\text{gr cm}^{-2}$  foils from several, low atomic number, refractory materials viz: Alumina, Aluminium Nitride, Pyrolytic Boron Nitride and Vitreous Carbon.<sup>9</sup> The Fulmer Institute have shown that large area foils of uniform thickness can be made from Alumina and Vitreous Carbon and can be formed on the material of the support frame.

Alumina foils are produced by masking an area of aluminium, anodising the remaining surfaces in a weak electrolyte, removing the mask and dissolving the aluminium from the oxide film.

Vitreous Carbon foils are made by uniformly coating copper with a sub-micron thick organic film, pyrolysing in an inert atmosphere, and then dissolving copper from the carbon film.

The majority of films made to date have been alumina 'windows' ie. supported around the complete periphery. A few  $50 \mu\text{gr cm}^{-2}$  alumina foils have been made with a long unsupported edge, but these have split at the unsupported edge at the end of the production process. The work is now being moved back to the Rutherford Laboratory to develop the technique to produce a 120 mm unsupported edge.

One other material under investigation is a proprietary silicone-silica hybrid material, which may be applied as a coating to form thin, strong, high temperature and abrasion resistant films.<sup>10</sup>

### Proton Density Distribution

The proton phase-space density distributions resulting from the multi-turn stacking process have been studied for scheme a) for uniform, Gaussian, elliptic and parabolic distributions of the injected  $\text{H}^+$  ions. The final distributions are found to be virtually independent of the input distribution.

Injection of 250 turns gives a very peaky (approx quartic) distribution as shown in Figure 6.

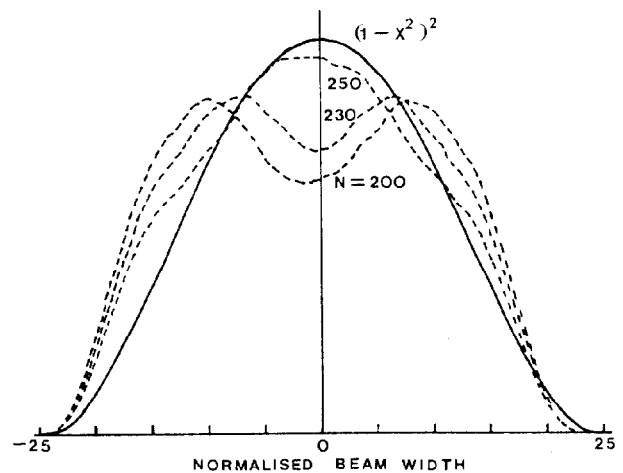


Fig 6: Radial Proton Density Distribution.

Delaying injection by a time equal to say 50 turns gives a hollow phase-space distribution and a flattened radial distribution as shown in Figure 6.

With the relatively low energy of the injected ions the beam coupling impedances are dominated by the very large space-charge reactive components. These reactive terms are distribution-dependent and the control of density distributions could be helpful in minimising beam instability problems. Controlling density distributions in this way will place greater demands on the current from the Linac. Also only particles with large amplitude betatron oscillations are injected and since similar distributions may be obtained in the vertical plane, the beam in the synchrotron is essentially rectangular in cross-section. Such beams may be injected into the SNS since a rectangular aperture is required to accept the large amplitude vertical motion of the early injected turns and to allow untrapped beam which spirals in during the acceleration cycle to be collected on a scraper system.

### Acknowledgements

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