STATUS OF THE SNS INJECTION SYSTEM*

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Abstract The 1-GeV 1-MW Spallation Neutron Source requires 1160-turn H^- foil injection into an accumulator ring with uncontrolled beam losses < 0.02%. The current status of the SNS injection system is discussed.

INTRODUCTION

The Spallation Neutron Source, SNS, is the next US neutron source for condensed matter physics [1]. The SNS consists of a 35-mA peak-current H^- front end, a 1.0-GeV 60-Hz proton linac operating at a 6% duty factor, and a 221-m-circumference accumulator ring. The ring will be filled with 1160-turn H^- foil-stripping charge-exchange injection. The 1-ms pulses from the linac will be compressed to 600 ns containing $1x10^{14}$ protons, producing short-pulse neutrons from a 1-MW liquid Hg target. Uncontrolled beam loss is a major concern. For hands on maintenance a full-energy loss of <1 nA/m is required, that corresponds to an integrated uncontrolled beam loss in the ring of less than 2×10^{-4} for 1-MW.

The ring will have a four-fold lattice with straight sections for injection, extraction, RF, and beam scraping. Each superperiod contains a 90^0 arc with a 2π phase advance consisting of four FODO cells, and a dispersionless straight consisting of two 11.586-m FODO cells. The straights phase advance will be adjusted to set the horizontal and vertical tunes to 5.82 and 5.80. Each 4.0-m arc half-cell will consist of a 0.50-m quad, 1.55-m drift, 1.50-m dipole, and 0.45-m drift.

The injected beam will be painted to have a horizontal and vertical full emittance, without space charge, of 120 π mm-mrad into the ring acceptance of 360 π mm-mrad. The ring will also accept a momentum spread of ±1%. Most quad bores will be 20 cm; however, the quad bores at the center of the arcs will be 30 cm for momentum dispersion and the quad bores in the center of the straights will also be 30 cm to allow for the injection orbit bumps and extraction displacements.

BEAM LOSS FROM INJECTION

Most of the H^- ions will be stripped to H^+ ions at the foil; however, a fraction will exit the foil as neutral H atoms. Recent measurements for H^- stripping in carbon [2] predict 0.8, 2.0 and 10% of the incoming H^- ions will emerge as H^o for 400, 300 and 200 $\mu g/cm^2$ thick foil, respectively. These H^o are not all in the ground state [3], but are distributed amongst excited states ~ $n^{-2.78}$, where n is the principle quantum number. Because the H^o must pass through a magnetic field to separate the H^-, H^o and H^+, the excited neutrals $H^{o}*$ can be stripped to H^+ by the Stark effect. For magnetic fields herein, the excited states with $n \geq 6$ have short stripping lifetimes and decay instantaneously after the foil to be captured into the ring acceptance with the H^+. States with $n \leq 3$ have long stripping lifetimes and survive to be transported along with the ground state H^o into a beam dump. However, n = 4 and 5 states have the potential of decaying in flight in the magnetic field downbeam from the foil so that their resultant trajectories do not lie within the ring acceptance, leading to uncontrolled beam loss.

To reduce this loss, the foil will be situated in the falling fringe field of a tapered-edged 0.30-T dipole magnet with a 20-cm gap. After passing through the foil, any $H^{o}*$ are exposed to a continually decreasing field. The foil will be placed at a position which has a magnetic field around 0.25 T, corresponding to the gap between the n = 4 and 5 states. The shorter lived n = 5 states quickly decay inside the acceptance. As the $H^{o}*$ continue downbeam, the remaining n = 4 state lifetimes increase reducing their probability of stripping.

Calculations were done to reduce this $H^{o}*$ loss, using a simple model similar to Ref. 4. $H^{o}*$ lifetimes were calculated as a function of magnetic field using a 5th order expansion formula [5]. These lifetimes were calculated for each allowed states for n= 4 (10 sub-states) and n=5 (15 sub-states). The populations were distributed as $n^{-2.78}$ amongst the n states, and uniformly for sub-states. Each sub-state population was tracked down the magnetic field profile, with its lifetime continually updated.

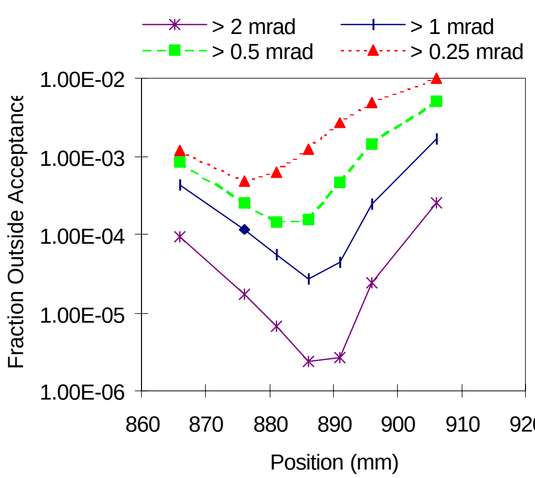
For a given critical deflection angle, the loss fraction was calculated from the difference between the populations of the remaining $H^{o}*$ at the longitudinal position corresponding to the critical deflection angle and at the final field location. This critical deflection angle was set at 1 mrad, since for a normalised linac beam rms emittance of 0.14 π-mm-mrad and ring emittance of 120 π-mm-mrad, there is about 1 mrad available between the linac beam spot and the desired ring acceptance. The total magnetic deflection experienced by initially stripped ions is also very important and was 0.49 ^{o}.

$H^{o}*$ loss fractions for the baseline design are shown in Fig. 1. For a foil located 875-mm from the dipole edge, the uncontrolled losses are $<10^{-4}$ of the n = 4 and 5 populations. This loss is not sensitive to the exact foil placement as compared to a foil in a constant field. The actual $H^{o}*$ loss as a percentage of the total injected beam is smaller than shown in Fig. 1. Only 1 to 10% of the exiting beam remains as H^o, and only 2.6% of these neutrals are in the n = 4 and 5 states. Consequently the uncontrolled loss arising from the stripping of the $H^{o}*$ n = 4 and 5 state outside of the ring acceptance is < 10^{-6} of the injected beam. These results are summarised in Table 1.

Table 1. Uncontrolled beam loss fractions calculated using calculated H^{o*} lifetimes (case 1) and artificial uniformly distributed H^{o*} lifetimes (case 2).

Case	Total H^o after foil	Fraction of H^o in n=4,5	Fraction of n=4,5 lost	Total loss fraction
1	0.01→0.1	0.026	10^{-4}	$3x10^{-7}$→$3x10^{-8}$
2	0.01→0.1	0.026	0.017	$4x10^{-5}$→$4x10^{-6}$

Fig. 1 Loss fractions for a foil located in a fringe field of a tapered-edge dipole with a maximum field of 0.31 T. Losses are shown for several critical angles.



Losses were also calculated for an artificial case with no lifetime gap between the n =4 and 5 states as a function of field. A lifetime shape was evenly distributed amongst 25 artificial excited states ranging from the shortest lived n = 5 state to the longest lived n = 4 state. This corresponds to a situation in which we have much less information on lifetimes. Without a gap about 1.7% of the n = 4 and 5 $H^{o}*$ are lost. This still gives a total loss fraction of < 4 x 10^{-5}. Uncontrolled beam loss from $H^{o}*$ decay will not be a major factor for SNS injection.

The H^- ions that miss the foil during normal operation and the H^- ions during a broken foil must be transported to the beam dump. The foil area will be chosen such that about five-rms emittance or 2% of the incoming linac beam in the distribution tails miss the foil. Assuming a 0.14 π mm mrad unnormalized rms linac beam emittance requires an 8 x 4-mm carbon foil. This loss is controlled and will not cause ring activation.

Coulomb and nuclear scattering from protons continuously traversing the foil can be a substantial uncontrolled beam loss, which is proportional to the foil thickness and the amount of circulating beam hitting the foil. This loss is about 6 x 10^{-6} per average foil transversals or "hits" per proton for a 300 μg/cm^2 foil.

INJECTION STRAIGHT SECTION

A schematic if the injection straight is shown in Fig. 2, which contains a three dipole chicane to form a fixed 8.0-cm horizontal orbit bump. The foil will be situated in the fringe field of the second chicane dipole giving the beam a 0.49^0 bend. This fixed orbit bump disturbs the lattice symmetry and creates a 30-cm dispersion in all the straight sections. The injection chicane is positioned such that the first (IDH1) and second (IDH2) dipoles will be placed upbeam of the central 30-cm focussing quad and the third (IDH3) dipole will be placed downbeam of this quad. IDH2 will be a 0.30-T C magnet, with the stripping foil located at the 0.25-T field region of the magnet edge.

The injection beam line from the linac contains two dipoles that direct the H^- beam into the foil. The first (HDH14) is a 1.9^0 0.776-m dipole and the second (HDH15) is a 7.6^0 2.5-m 0.30-T05-mm-thick septum. The beamline for controlled loss to the injection dump begins at the end of the 2.0-m 0.5-T H^+ and H^0 septum (DDH1).

Two sets of pulsed kickers, four for each plane (IKH1 to IKH4 and IKV1 to IKV4) will create the dynamic orbit bumps to paint a phase space distribution from the injected protons. These magnets have < 0.1-T fields, and ferrite cores will be used with rectangular-frames and square aperture to minimise losses. The magnets will be installed outside of the vacuum chamber, which could be fabricated from either a thin high-resistivity material such as inconel or metallized ceramic. These dipoles will operate with either programmable or current-decay PSs. Current-decay PSs are highly reliable and uses a DC PS to charge-up the magnet inductance, which at the appropriate time is switched is to a passive external resistor. The magnetic field follows the stored current, which decays exponentially with a time constant determined by the magnet inductance and the resistor

H^o emerging from the foil will be converted to protons by a thick foil. The downbeam quad bends the H^- into the 0.5-T septum, but because of the high magnetic field a small fraction will be stripped to H^o. If a thick foil is placed in their path inside the septum, they will be converted to protons. Placement of the foil will be determined after measurement of the magnetic field, so that the median of the protons emerging from the septum will be parallel with the protons from the H^o. The plan is to place the foil inside the magnet where the field integral is equal to the field integral travelled by the H^-.

Electrons stripped from the H^- beam will curve with a 1.2-cm radius inside the 0.25-T field, and be intercepted by a Cu block that is placed 0.5-cm downbeam and 2.4-cm radially outward from the foil.

The electron power will be about 1 kW and the Cu block water-cooled. Secondary electrons will not emerge from the Cu block since it is located inside a 0.25 T field.

INJECTION OPTIMISATION

Because of its resiliency and high sublimation temperature, ~3500 C°, a carbon stripper foil will be used and heated by the energy deposited by the proton and two accompanying electrons. The corresponding heat may limit the beam intensity from H^- foil injection. There is no data available for what fraction of the energy loss contributes toward foil heating, consequently 100% is assumed. The maximum foil temperature is determined by the peak current density of the linac beam. The average linac macropulse current for 1-MW at the injection foil is 18.2 mA. With an rms emittance of 0.14 π mm-mrad in both planes and HEBT 16-m horizontal and 5-m vertical beta functions, the peak current density at the foil is 3700 A/m^2. The temperature at the beam spot will rise quickly toward equilibrium until the heat input (~ foil thickness) and black body radiation become equal. Detailed ANSYS calculations predict peak temperatures of 2546 and 3305 K°, for to 220 and 400μg/cm^2 foils, which indicate carbon foils up to 400 μg/cm^2 may survive injection. However, the foil breakage mechanism is more complicated than just simple foil evaporation and more detailed calculations and experiments are necessary. A foil thickness around 300 μg/cm^2 may be used.

The final emittance distribution in the ring is achieved by bumping the closed orbit at the foil during injection. Three different bump schemes have been investigated: bumping only in the horizontal plane giving a vertical phase space “smoke-ring” distribution; correlated bumps in-which the horizontal and vertical closed orbits are both moved away from the foil; and anti-correlated bumps in which the horizontal orbit is moved away from the foil, and the vertical orbit is moved towards the foil giving a “K-V like” final distribution. Exponential time dependencies are assumed for all cases. Optimisation calculations were performed to determine the initial bump offset, the bump e-fold decay times, and the linac beam spot size, in order to minimise foil traversals, minimise the maximum tune spread, and constrain the foil temperature to 2750 K.

Table 2 lists results for a 2 MW beam, with 1% of the injected beam missing the foil. Correlated bumping in both the horizontal and vertical directions reduces the foil traversals by half compared to the “smoke ring” and “anti-correlated” painting schemes. All cases have maximum tune spreads of ~ 0.25. The current status of the SNS injection system has been described. Additional calculations and optimisations are underway.

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Table 2 Injection optimisation results.

Painting scheme	Foil hits / p	NES loss 10^{-4}	$\Delta\nu_x$	$\Delta\nu_x$	No. of x,y e-folds	Initial x,y bump (mm)	Linac β_x, β_y (m)
Y smoke ring	5.5	0.32	0.25	0.24	1.2, 0	10.7, NA	19.4, 8.5
Correlated x-y	2.7	0.16	0.18	0.24	6.9, 1.3	6.3, 4.1	25.9, 5.5
Anti-correlated x-y	5.0	0.29	0.24	0.17	1.5,1.3	2.6, 9.4	15.5, 9.5

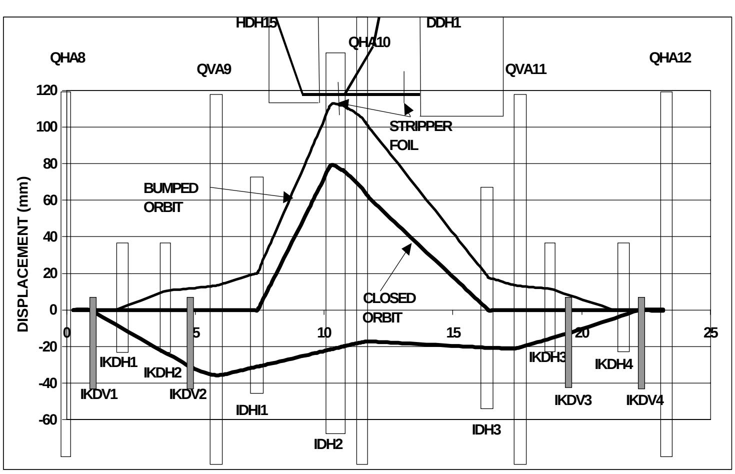

Fig. 2. Orbit bumps in the SNS Injection region.

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