INJECTION INTO THE SNS ACCUMULATOR RING: MINIMIZING UNCONTROLLED LOSSES AND DUMPING STRIPPED ELECTRONS

D. T. Abell, Y. Y. Lee, W. Meng, BNL, Upton, NY 11973, USA

Abstract

At injection into the 2 MW Spallation Neutron Source Accumulator Ring, one serious concern is beam loss caused by magnetic stripping of excited H\textsuperscript{0} Stark states. The injection magnet described here minimizes this beam loss by taking advantage of a gap in the ionization rates between the \( n = 4 \) and \( n = 5 \) Stark states. Also described here is the plan for removing the 2 kW of stripped electrons without affecting the ring acceptance.

1 INTRODUCTION

The Spallation Neutron Source (SNS) will be a high-intensity pulsed neutron source comprising a 52 mA peak-current H\textsuperscript{−} ion source; a 1.0 GeV proton linac; and a 248 m accumulator ring; a Hg target; and associated transfer lines. Both ion source and linac will operate at 60 Hz with a 6% duty factor. Using charge-exchange injection, the accumulator ring will take 1100 turns to compress a 1 ns linac pulse into a 700 ns bunch with \( 2.1 \times 10^{14} \) protons. The design for the accumulator ring uses a four-fold-symmetric lattice with straight sections for injection, collimation, extraction, and RF bunching. The ring will have an acceptance of \( 480 \pi \text{mm} \cdot \text{mr} \), and the injected beam will be painted to horizontal and vertical emittances of \( 160 \pi \text{mm} \cdot \text{mr} \). Space-charge forces will increase the emittance somewhat, and adjustable collimators placed at about \( 230 \pi \text{mm} \cdot \text{mr} \) will be used to control the associated halo. Further details of the accumulator ring are given elsewhere in these proceedings [1].

Because of the unprecedented 2 MW beam power, beam loss is a serious concern: The need to keep the fractional uncontrolled beam loss below \( 10^{-4} \) has been one of the principal design considerations for the entire ring [2]. Losses in the injection straight can arise when H\textsuperscript{−} ions strip incompletely and exit the foil as neutral hydrogen, H\textsuperscript{0}. In the magnetic fields typical of the SNS, these neutrals can strip spontaneously and therefore represent a significant potential source of uncontrolled beam loss.

2 THE INJECTION STRAIGHT

The SNS accumulator ring’s injection straight (see the schematic in Fig. 1) will use a fixed four-dipole chicane to produce a 100 mm horizontal orbit bump. Two sets of fast kickers, four in each plane, driven by programmable power supplies, will create the dynamic orbit bumps required for phase-space painting. The quadrupole magnets on either side of the fixed chicane will have a narrow profile, with flux being returned only at the top and bottom, to accommodate the injection line from the linac. H\textsuperscript{−} ions from the linac will enter the ring through a 2 kG injection septum, traverse the second chicane magnet, and strike the stripper foil, in the downstream fringe of that magnet, at a point where the magnetic field \( B_{\text{foil}} = 0.25 \text{T} \). Ions which either miss the stripper foil or emerge as H\textsuperscript{0}’s will be converted to protons through a thick stripping foil and then sent to the injection dump.

Figure 2 shows the two C-magnet dipoles, C1 and C2, in the middle of the fixed chicane. The upstream magnet, C1, is on the right, and the stripper foil will sit in its downstream fringe field.

Figure 1: Injection straight in the SNS Ring: fixed-chicane magnets (red); horizontal (green) and vertical (yellow) fast kicker magnets; ring quadrupoles (blue). Injection takes place in the downstream fringe of the second fixed-chicane magnet.
The neutrons that exit the foil will populate the various hydrogen eigenstates $|n\rangle$, where $n$ denotes the principal quantum number. Because of the magnetic field, an $H^0$ will see, in its frame of reference, an electric field that splits the degenerate eigenstates into many Stark states, each with a different ionization rate [6]. At the injection point, the magnetic field is $B_{\text{foil}} = 2.5 \, \text{kG}$. In this case Stark states with $n \geq 6$ have very short stripping lifetimes: those $H^0$'s will decay as soon as they leave the foil and will enter the beam core along with the protons. And Stark states with $n \leq 3$ have relatively long stripping lifetimes: those $H^0$'s will survive all the way to the second stripper foil.

The $n = 4$ and $5$ Stark states can decay in flight, and those $H^0$'s can contribute to beam loss at injection. However, a significant gap in lifetimes between the $n = 4$ and $n = 5$ states makes it possible to minimize this loss by choosing $B_{\text{foil}}$ within this gap: the shorter-lived $n = 5$ states will decay very rapidly, well inside the beam emittance; and the $n = 4$ states will survive much longer, reducing the number lost. We can further reduce this loss by placing the stripper foil in the downstream fringe of the injection magnet C1: $H^0$'s in the $n = 5$ states will still decay before they see the magnetic field fall; and almost all $H^0$'s in $n = 4$ states will survive until after they see a lower magnetic field, at which point their lifetimes become much longer.

To estimate the beam loss at injection, we assume the excited Stark states to be populated according to $n^{−2.78}$, but uniformly for fixed $n$. Hence about 1.7% of the $H^0$'s will be in one of the 10 Stark states with $n = 4$; and about 0.9% of the $H^0$’s will be in one of the 15 Stark states with $n = 5$. The longitudinal location $z_{\text{foil}}$ at which an $H^0$ strips, relative to the foil location $z_{\text{foil}}$, determines the angular error $\theta$ of the newly created proton: $\theta = \frac{1}{2} \rho \int_{z_{\text{foil}}}^{z_{\text{foil}}(\theta)} B_y \, dz$. Using numerical integration, one can invert this expression to obtain $z_\theta$ as a function of $\theta$. Then the fraction of $H^0$'s that decay from a given Stark state into a trajectory with an angular error of at least $\theta$ is

$$
\int_{z_{\theta}(\theta)}^{\infty} \exp \left( - \frac{z - z_{\text{foil}}}{v_0 \tau(B(z))} \right) \frac{dz}{v_0 \tau(B(z))}
$$

where $v_0$ denotes the $H^0$’s speed; and $\tau(B)$ denotes the field-dependent lifetime of the given Stark state [6], computed using a fifth-order analytic formula. After evaluating this integral for the different Stark states and weighting the results according to their relative populations, we obtain the final results shown in Fig. 4: the fraction $f$ of $H^0$’s exiting the foil that strip at or outside a given angular error $\theta$ (in mr).

The injection painting schemes proposed for the SNS accumulator ring [7] paint the horizontal phase space from the inside out. Using the lattice function values at the foil and the emittances of the circulating and injected beams, one can show that the injection process will tolerate an angular error of 4 mr at the beginning, and 1 mr at the end. Any $H^0$ that strips with a smaller angular error will be captured in the beam core.
Figure 4: Fraction $f$ of $H^0$’s exiting the foil that strip outside a given angular error $\theta$ (in mrad).

The actual beam loss caused by delayed stripping of $H^0$’s will, of course, depend on the details of the horizontal injection bump; but Fig. 4 says that for most reasonable bumps the fraction of $H^0$’s that strips outside the core of the beam will lie in the range 0.5–1%. Since only 1–10% of the incident beam will exit the foil in the $H^0$ charge state, it follows that the fractional beam loss caused by delayed $H^0$ stripping should lie in the range $0.5 \times 10^{-5}$–$1.0 \times 10^{-4}$. Most of this beam loss will be captured by the collimators [8]; only a small fraction—depending on the collimator efficiency—will contribute to the uncontrolled beam loss budget.

One can improve the stripping efficiency, and hence lower the above-described beam loss, by using a thicker foil. However, the stripping of $H^-$ ions and the impact of circulating protons both deposit energy in the foil proportional to the volume involved, whereas the foil radiates energy proportional to its surface area. Hence thinner foils operate at lower temperatures and last longer. The choice of foil thickness will therefore involve a balance between foil lifetime and stripping efficiency.

4 REMOVING STRIPPED ELECTRONS

Stripped electrons will have the same velocity as the protons and, hence, a kinetic energy 545 keV. In the local field $B_{foil} = 2.5$ kG these electrons will have a gyration radius $\rho = 1.23$ cm. As a consequence, a typical electron catcher, placed in the horizontal plane of the foil, would severely restrict the ring acceptance. To circumvent this problem, we take advantage of the fact that the foil lies above the centre of the helical trajectories meets the bottom of the vacuum chamber along a series of lines that radiate outward from where the center of the helical trajectories meets the bottom of the vacuum chamber.

To decide the details of the electron catcher, we have used OPERA-3d to compute the helical trajectories for stripped electrons launched in a six-sigma range about the design orbit of the injected $H^-$ beam. A vane’s height is limited by the ring acceptance; and the separation is determined by the helical pitch. The vanes will then be placed along a series of lines that radiate outward from where the center of the helical trajectories meets the bottom of the vacuum chamber.

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REFERENCES