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

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Abstract

At injection into the $2\,\mathrm{MW}$ Spallation Neutron Source Accumulator Ring, one serious concern is beam loss caused by magnetic stripping of excited H^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 $2\,\mathrm{kW}$ 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 $52\,\mathrm{mA}$ peak-current H^- ion source; a $1.0\,\mathrm{GeV}$ proton linac; and a $248\,\mathrm{m}$ accumulator ring; a Hg target; and associated transfer lines. Both ion source and linac will operate at $60\,\mathrm{Hz}$ with a $6\,\%$ duty factor. Using charge-exchange injection, the accumulator ring will take 1100 turns to compress a $1\,\mathrm{ms}$ linac pulse into a $700\,\mathrm{ns}$ bunch with 2.1×10^{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 $480\pi\,\mathrm{mm}\cdot\mathrm{mr}$, and the injected beam will be painted to horizontal and vertical emittances of $160\pi\,\mathrm{mm}\cdot\mathrm{mr}$. Space-charge forces will increase the emittance somewhat, and adjustable collimators placed at about $230\pi\,\mathrm{mm}\cdot\mathrm{mr}$ 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 $2\,\mathrm{MW}$ 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^- ions strip incompletely and exit the foil as neutral hydrogen, H^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 $100\,\mathrm{mm}$ 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 accomodate the injection line from the linac. H^- ions from the linac will enter the ring through a $2\,\mathrm{kG}$ 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 $B_{\mathrm{foil}} = 0.25\,\mathrm{T}$. Ions which either miss the stripper foil or emerge as H^0's will be converted to protons through a thick stripping foil and then sent to the injection dump.

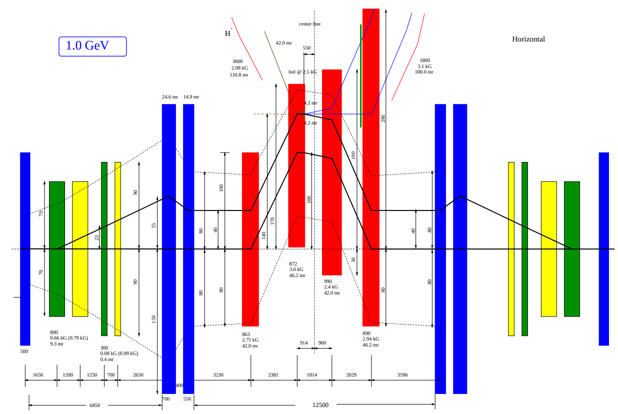

Figure 1: Injection straight in the SNS Ring: fixed-chicane magnets (red); horizontal (green) and vertical (yellow) fast kicker magnets; ring quadrupoles (blue). Injection takes place in the downstream fringe of the second fixed-chicane magnet.

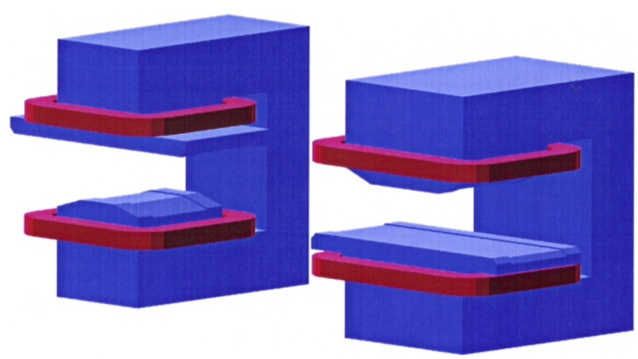

Figure 2: The two C-magnets, C1 and C2, in the middle of the fixed chicane. The upstream magnet, C1, is on the right, and the stripper foil will sit in its downstream fringe field.

Figure 2 shows the two C-magnet dipoles, C1 and C2, in

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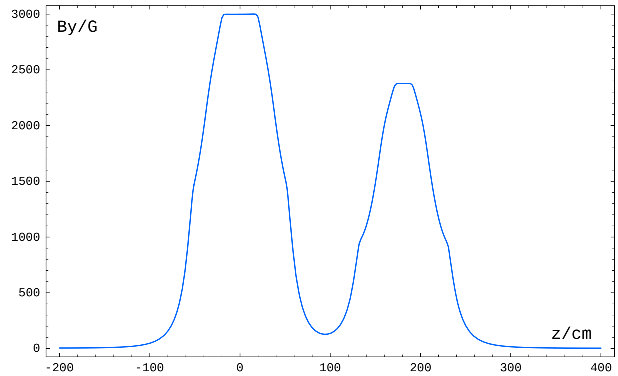

Figure 3: Longitudinal profile of the field B_y in the chicane magnets C1 and C2. The origin $z = 0$ is at the center of C1, and the foil will be at $z_{\text{foil}} = 30.7\,\text{cm}$.

the middle of the fixed chicane, and Fig. 3 shows the field profile through those two magnets. Their unusual design derives from several constraints, including the following:

- The dipole field integrals through C1 up to the foil and from the foil through C2 must cancel the dipole field integrals through respectively the first and last fixed-chicane magnets.
- The relative variation of the integrated strength through C1 and C2 should not exceed 5×10^{-4} across the ring acceptance.
- To avoid Lorentz stripping the injected $1.0\,\text{GeV}$ H^- ions, the peak field in C1 may not exceed $3.0\,\text{kG}$. And to minimize beam loss caused by subsequent Lorentz stripping of H^0's, the magnetic field at the foil should be $2.5\,\text{kG}$, and the peak field in C2 should not exceed $2.4\,\text{kG}$. (See Section 3.)
- To prevent stripped electrons from returning to strike the foil, the magnetic field line at the foil must tilt upstream of vertical by at least $65\,\text{mr}$. In addition, the field at the electron catcher should not exceed that at the foil. (See Section 4.)

Because their fringe fields overlap, these two magnets have been modeled as a unit using OPERA-3d [3].

3 MINIMIZING INJECTION LOSSES

The foil will completely strip most injected H^- ions. But recent measurements predict that, for carbon foils in the range 200–400 $\mu\text{g}/\text{cm}^2$, 0.8–10 % of the H^- will emerge as H^0 [4]. As those neutrals pass through the magnetic field required to separate the different charge states, they can be stripped by the Lorentz force; and, depending on when they strip, their subsequent trajectories can lie outside the beam core. To minimize this source of beam loss, we will use a modified version of the strategy first described by Jason, *et al.* [5].

The neutrals 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_{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_s at which an H^0 strips, relative to the foil location z_{foil}, determines the angular error θ of the newly created proton: $\theta = \frac{1}{B\rho}\int_{z_{\text{foil}}}^{z_s} B_y\,dz$. Using numerical integration, one can invert this expression to obtain z_s as a function of θ. Then the fraction of H^0's that decay from a given Stark state into a trajectory with an angular error of at least θ is

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

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 θ (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 $4\,\text{mr}$ at the beginning, and $1\,\text{mr}$ at the end. Any H^0 that strips with a smaller angular error will be captured in the beam core.

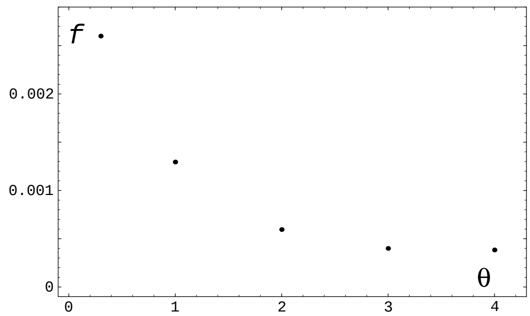

Figure 4: Fraction f of H^0's exiting the foil that strip outside a given angular error θ (in mr).

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 0.5×10^{-5}–1.0×10^{-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 $B_{\mathrm{foil}} = 2.5\,\mathrm{kG}$ these electrons will have a gyration radius $\rho = 1.23\,\mathrm{cm}$. 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 mid-plane in the downstream fringe field of the injection magnet: The initial velocity of the stripped electron can be resolved into components $v_\perp$ and $v_\parallel$, respectively orthogonal and parallel to the field lines at the foil. The dipole field has no effect on $v_\parallel$, but it causes $v_\perp$ to rotate about the field lines; hence the electron travels downward along a helical path. If we shape the field at the point of injection so that it tilts upstream of vertical by at least 65 mrad, then the electron will clear the lower edge of the foil, 4 mm below injection, within the first turn of its cyclotron motion. For the magnet shown in Fig. 2, the field angle is about 220 mrad, which more than satisfies the requirement.

From the stripped electron's point of view, the fringe field region of the usual dipole magnet has the characteristics of a magnetic bottle: the field strength is stronger at the top and bottom than in the middle. To ensure that stripped electrons are not reflected back upwards before reaching the collector, the lower pole face of C1, as shown in Fig. 2, is extended downstream about 20 cm (80% of the gap). The field lines intersecting the foil will therefore enter the lower pole face at roughly normal incidence, and the stripped electrons will not be reflected before reaching the collector at the bottom of the vacuum chamber.

The electron catcher must carry off the 4 mA of stripped electrons. In addition, however, it must remove the heat deposited by those electrons and prevent secodary electrons from interfering with the proton beam. To dissipate the 2 kW average power in the stripped electrons, a water-cooled copper insert will form the bottom of the vacuum chamber below the stripper foil. To address the problem of secondary electrons, a series of vanes will rise out of the copper insert, with walls that slightly overhang the surface struck by the stripped electrons. The secondaries will have only a few eV of energy and will therefore spiral tightly about the local magnetic field. The overhanging surface will then prevent them from escaping along those field lines and into the attractive potential of the circulating beam.

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.

5 ACKNOWLEDGEMENTS

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