Minimization of First-Turn Losses by Excited Neutrals in Charge-Changing Injection of Accumulator Rings

Andrew J. Jason, Barbara Blind, Paul J. Channell, and Tai-Sen F. Wang
Los Alamos National Laboratory
Los Alamos, NM 87545

Abstract

Substantial beam losses, due to production of excited neutrals by the foil stripper, will occur immediately after injection in proton accumulator rings that utilize charge-changing injection. A technique is proposed, based on experimental and theoretical results for excited-state production and stripping, that is potentially capable of reducing such losses by a factor greater than 10^4 at 800 MeV. In the technique, foil stripping occurs in a shaped magnetic field that resolves the excited atomic levels into stripped states that are within ring acceptance and unstripped states that can be ejected from the ring. An added magnetic-mirror-field configuration is proposed as an effective means of minimizing interactions between stripped electrons and the foil.

1. Introduction

Rings that accumulate protons for many turns to produce a high-intensity particle burst necessarily use charge-changing injection at a stripper foil. Several percent of the injected beam (depending on energy and foil thickness) leaves the foil as neutral hydrogen atoms. For the Los Alamos Proton Storage Ring (PSR) at 800 MeV and a 250-μg/cm^2 carbon foil, approximately 5% of the beam remains in the neutral state, with ~20% in excited states (H^{0*}) having principal quantum number n>3. Those excited atoms that do not undergo rapid radiative decay are susceptible to stripping in a downstream dipole magnet. Since the stored beam is deflected by the magnet, unless stripping is very immediate in the magnet fringe field, the stripped neutrals will lie outside the ring acceptance and eventually be lost during the first turn, producing intolerable activation in the ring components for high injection energies.

This phenomenon was first noted in the PSR (1,2) and further work is under way to quantify the excited-state production (3). Here we suggest an injection configuration that significantly reduces the problem. The scheme may be important for accumulator rings used in next-generation spallation-neutron sources. In this paper, parameters for a ring design developed at Los Alamos [4] for a 1-MW spallation-source driver are used as an example. A solution is suggested, as well as the amelioration of problems that arise.

2. Loss Reduction

It is possible to drastically reduce this "first-turn loss" by arranging injection so that the foil is located in a magnetic field of appropriate strength and distribution. Figure 1

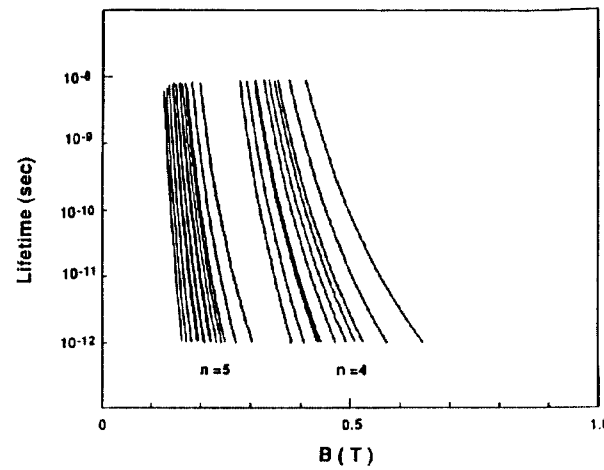

Figure 1. Plot of the state lifetime for field ionization versus magnetic field for the n=4 and n=5 states of the excited hydrogen atom. The two states nearest the gap, designated by their parabolic quantum numbers n, m, n1, n2, are 4,0,0,3 and 5,0,4,0. Fewer states than n^2 are seen because of degeneracies.

indicates the plausibility of such a scheme. Here, consider the sudden appearance of 800-MeV H^{0*} particles in a constant magnetic field of unlimited extent. The plot of state lifetimes, calculated using a fifth-order WKB expansion [5], versus magnetic field shows a gap in field between the very rapid ionization rate of the lowest state with n=5 and the slower ionization rate of the highest n=4 state. If the magnetic field at the point of H^{0*} creation is near 0.25 T, the lifetime of the lowest n=5 state is such that 1/e of the particles are ionized within about 0.3 mm. The particles that were instantaneously stripped to protons will have undergone a deflection of less than 0.012 mrad in the field before becoming stripped and are well within the stored-beam emittance. On the other hand, 1-1/e of the particles in the highest n=4 state will have traveled more than a meter before decaying, well outside a typical magnet. Higher-lying states will be stripped virtually instantaneously with consequent negligible deflection so that they join the stored beam. Conversely, lower states will be stripped much more slowly and will leave the magnet as undeflected excited neutrals, to be disposed of in a beam dump. Hence, it is expected that, at a field near 0.25 T, only the two states near the gap in

Work supported in part by the US Department of Energy, Office of Defense Programs and in part by the Los Alamos Laboratory Institutional Supporting Research.

Figure 1 will enter into consideration and that fine variation of the field in a finite-length magnet will produce a minimum in the number of those atoms that are ionized and lie between the trajectories of the neutral beam and the stored beam.

To implement these ideas, consider the configuration shown in Figure 2 for the ring injection chicane. The stored

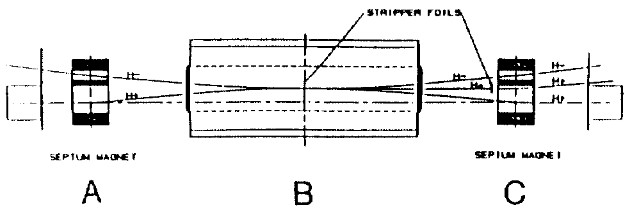

Figure 2. Plan view of the injection chicane for the Los Alamos accumulator-ring design. Septum magnets A and C are identical and have different fields in their two channels. Magnet B has an extra winding spanning 40 cm of its central section to create a region of higher field.

beam is bent through 5° by magnet A, oppositely through 10° by magnet B, and again through 5° by magnet C (identical to A) so that it travels colinearly with its entrance to A. The H^- beam being injected passes through the lower-field (below ~0.38 T to cause negligible field stripping of the H^-) region of A and is bent by B to merge with the stored beam at the center of B, where most of the beam impacts a foil, producing mainly protons. The H^- that miss the foil pass through the low-field region of C and are transported to a beam dump. The unexcited neutrals pass through a thick foil just before entering the high-field region of C and thence to a beam dump. Some fraction of the n=4 and 5 excited neutrals will be ionized by the field of B and will leave B on trajectories between the ring acceptance and the phase-space area that will be transported cleanly to the beam dump. These particles will be lost and we seek a field configuration in B that minimizes the loss. With proper choice of the injection point in phase space, the acceptance angle for the stripped neutrals can be extended to within 2 mrad of the injected beam.

To enhance the scheme and to keep the bend angle of B constant during loss optimization, we add a winding to the central section of B that allows addition of up to 10% to the field at the foil to form a peak in the magnetic field. The two fields can then be adjusted so that the maximum number of atoms with n=5 are stripped at an angle within the stored-beam emittance while a minimum number of n=4 states are stripped at all. In Figure 3 we show the sum of the fractions of the n=4 through 6 states that are stripped with angles to the injected beam of greater than 2 and 3 mrad during passage through B as a function of the main-winding excitation. For the right-hand curve, the central winding is unenergized while for the curve on the left hand the central winding is adjusted to keep the stored-beam deflection constant at 10°. In this latter configuration the loss is about 2×10^{-4}. Conservatively estimating the combined fraction of the states at about 1% of the injected beam, the first-turn losses have been diminished to about 2×10^{-6} of the injected beam. To account

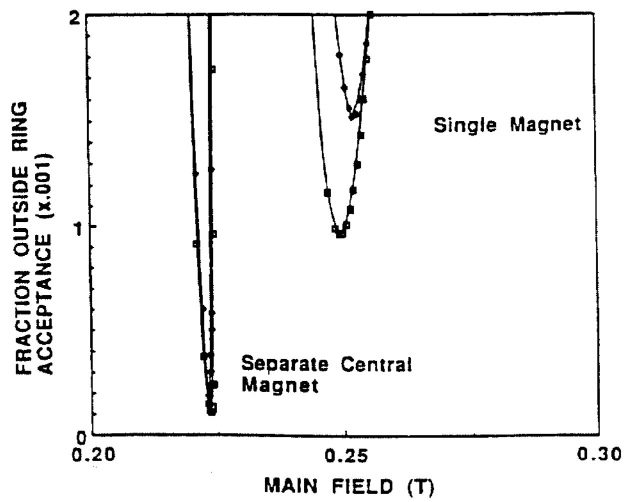

Figure 3. Sum of the fractions of the n=4 through 6 states stripped to protons that lie outside 2 and 3 mrad of the injected-beam centroid for two magnet configurations.

for items left out of the calculation (such as spatial variation of the magnetic field and lack of knowledge of state population) we assess first-turn losses at 1×10^{-5}. This places the beam loss due to this effect at 15 nA, mostly absorbable by a collimation system within the ring.

3. THE ELECTRON PROBLEM

The scheme for minimizing first-turn losses places the foil in a magnetic field. The two electrons stripped from each H^- atom each has a kinetic energy of 0.43 MeV and will be bent by the magnetic field in a circular path of radius ~1 cm, to return to the foil many times (~500 passes for complete energy loss). The energy deposition will heat a section of the foil beyond its vaporization temperature during one injection cycle. This situation is pictured in Figure 4.

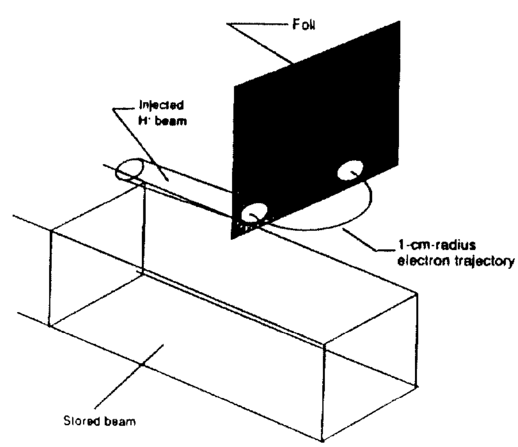

Figure 4. Relationship of injected-beam, stored-beam, and electron trajectories at the stripper foil.

To prevent this, a thick (greater than ~1 mm) and adequately cooled absorber could be placed to extend within

2 cm of the injected-beam impact point on the foil. The absorber will have to withstand about 1.2-kW average power over millimeter-sized dimensions. While this may be possible with refractory materials and very large coolant flows, the absorber will also produce undue scattering of the stored-beam fringes. A rotating carbon disc provides a more conservative solution in terms of thermal transfer. A 10-cm-diameter disc rotating at ~1 rev/s would provide sufficient radiative area to keep the disc below 1500°C. However, the scattering problem remains. Increasing the beam energy would increase the radius of electron motion and promote the feasibility of removing the electrons' power.

A potential difference of, say, 10 kV might be placed across the chamber, with the foil biased at some intermediate potential, to remove the electron from the foil. However, boundary conditions, including the beam potential, are complex for this problem and we have not completed the analysis of how rapidly the electrons are deflected downward from the foil. Several strikes are indicated, possibly inadequate to preserve foil integrity.

Consider, instead, placing a circular coil at the upper poles of the injection magnet, centered at the electron trajectory, to create a "mirror" field. The coil (including images induced in the magnet poles) will produce field lines that diverge from the coil. Imagining now a cylindrical coordinate system (with z axis along the primary dipole field), a radial component of the field is developed that provides a downward force on the electrons. The field is expressible in terms of a series of elliptic integrals. For a 6.5-cm-radius coil with 7 kA-turns, a radial field of 30 G is created at the electron orbit. This translates to an electric field near 0.8 MV/m for an 800-MeV H^- beam. The resulting electron trajectory is shown in Figure 5. The effect on the foil temperature is now small.

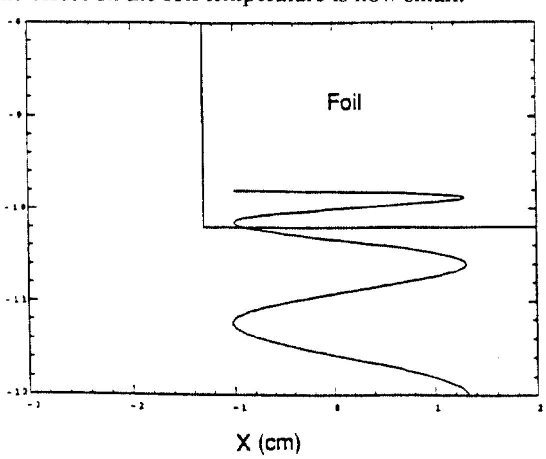

Figure 5. Trajectory of an electron created at the center of the injected beam. The view is in the foil plane.

The solution appears complex but feasible. Analysis of the mirror magnet indicates that a single-turn coil can be constructed to carry the necessary current. Note, however, that the field configuration is off center from the stored beam and promotes a host of multipole components, both skew and normal. By integrating the field over the beam direction, the multipole components can be calculated. For our parameters, the quadrupole moment predominates with multipole coefficients of 0.021 T and 0.027 T for the normal and skew coefficients, respectively. Other components are negligibly small. Tracking calculations show small effect on the beam for the short accumulation time considered. Correction of the multipoles by adding quadrupole magnets at the ends of the central magnet may also be done. However, the mirror field variation over the injected beam extent increases the minima in the left-hand curve of Figure 5 by about a factor of five.

4. Alternative Solution

One can consider placing the foil in a field-free region and attempting to strip the excited atoms in an optimum manner by a downstream magnet with an open yoke, located near an extended beam dump so that particles stripped in the magnet field would be captured. Figure 6 shows a calculation of the particles that are stripped with angles between 2 and 20 mrad of the stored beam, for a 1-m-long magnet with fringe-field effects included. These particles are presumably lost in the ring. The absolute value of the loss shown is uncertain because of uncertainties in the state populations, but may be roughly calibrated by the PSR loss at 1.2 T. The configuration is thus not highly effective.

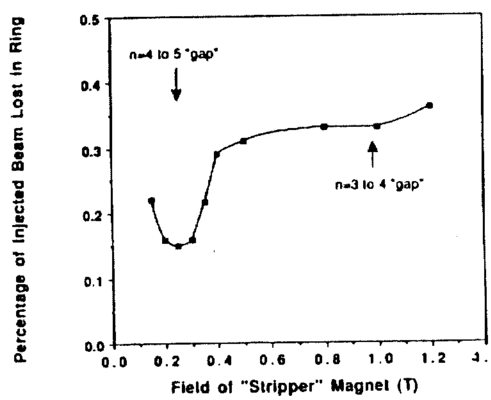

Figure 6. Ring loss of 800-MeV foil-excited neutrals from passage through a 1-m-long magnet as function of the magnet field.

5. References

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