Theoretical Study of H⁻ Stripping with a Wiggler Magnet

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Abstract

The first step for injecting protons into the LAMPF Proton Storage Ring (PSR) at LANL is to strip a beam of 800-MeV H⁻ ions to H^0 with a 1.8-T dipole magnet. Because of the finite lifetime of energetic H⁻ ions in the magnetic field, their trajectories bend before stripping causing the angular spread of the beam, and therefore its emittance, to grow during the stripping process. In the case of the PSR, the horizontal beam emittance grows by a factor of roughly three during injection. As a consequence, beam losses in the ring are significantly greater than they would be if there were not emittance growth. A speculative technique is proposed in which the beam divergence growth and resulting emittance growth is reduced by stripping the H⁻ in a wiggler magnet whose transverse field alternates in direction as a function of position along the beam axis. The wiggler field configuration is adjusted so that the angular beam spread introduced during passage through one unidirectional-field increment of path is relatively small and so that 99.99% of the beam is stripped after passing through the whole magnet. With careful field design the net added angular beam spread is reduced because the incremental angular spreads are painted back and forth over the same small range. In the hypothetical case described, the calculated emittance growth and beam loss increase are significantly smaller than those calculated for a conventional stripper magnet.

I. INTRODUCTION

The PSR, shown in Figure 1, is filled with protons in a two-stage process. First 800-MeV H⁻ ions in the injection line are stripped to H^0 with a 1.8–Tesla dipole stripper magnet; the H^0 are then stripped to H^+ by passing through a 200-μg/cm² carbon foil in the ring itself. After the ring is filled, the stored protons are extracted and transported to the neutron production target at the Los Alamos Neutron Scattering Center (LANSCE).

The H⁻ stripping process has an unwanted side effect in that it leads indirectly to unwanted losses of beam circulating in the PSR; the beam is lost through collisions of protons in the tails of the stored beam with limiting apertures in the ring. The resulting activation of ring components makes ring maintenance more difficult. How does the H⁻ stripping process lead to this problem? H⁻ stripping in a magnetic field is a probabilistic process described by a field-dependent ion lifetime; therefore, ions travel a finite distance before being stripped. Because the stripper magnet field is vertically pointing, the trajectory of an H⁻ will be deflected through some angle in the horizontal plane before being stripped. Since the stripping per unit path length is probabilistic, the angles through which a collection of H⁻ ions are deflected before being stripped will cover a range. Figure 2 illustrates

this. This additional angular spread added to the inherent divergence of the incoming H⁻ beam causes the horizontal-plane emittance of the H^0 beam to be larger than that of the

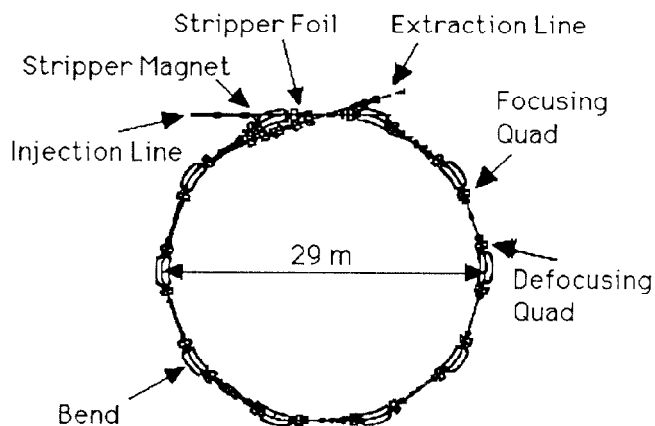Figure 1. Layout of the LANL Proton Storage Ring.

original H⁻ beam. If this emittance growth were reduced, the stored-beam size, which increases as the emittance of the injected H^0 increases, would be made smaller, and beam losses, which increase with beam size, would be reduced.
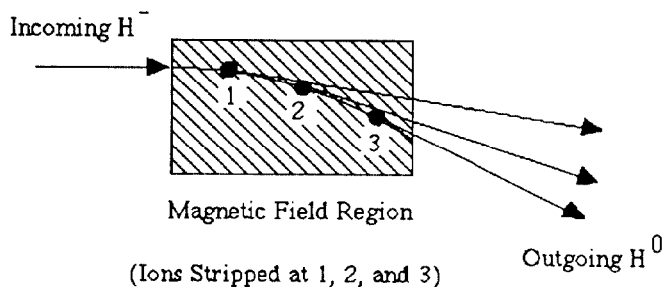

Figure 2. Illustration of H^0 Angular Spread Resulting from Spread of H⁻ Lifetimes in Magnetic Field Region.

In the next section, a speculative scheme is proposed to reduce the emittance growth during H⁻ stripping by the use of a magnet whose field transverse to the beam direction alternates in direction as a function of distance along the beam. This type of magnet is commonly referred to as a wiggler magnet in synchrotron-light-source or free-electron-laser systems. In section III, theory relevant to H⁻ stripping and emittance growth is discussed, while section IV contains results of divergence growth calculations based on the theoretical formulas. Calculated PSR beam losses derived from results of the divergence growth estimates are discussed

in section V. In the last section practical considerations regarding wiggler magnet construction are mentioned briefly.

II. REDUCTION OF BEAM DIVERGENCE GROWTH WITH A WIGGLER-MAGNET STRIPPER

In the present PSR stripper magnet the incoming H^- ions see a field that rises rapidly from zero to 1.8 Tesla. Special effort was made to design the magnet so that this rate of rise was as large as possible [1] since, for this case in which all the beam is stripped to H_0 in the fringe field region, the faster the field rises the smaller is the divergence added to the beam because of H^- trajectory deflection before the ion is stripped.

The proposal that divergence growth could be reduced by stripping with a wiggler magnet hinges on the idea that, instead of stripping all the beam as rapidly as possible, as is done with the present PSR stripper magnet, stripping could be spread out over a cascaded series of relatively weak field segments, in any one of which only a fraction of the beam would be stripped, and for any one of which a relatively small range of divergence angles would be introduced. If the fields in successive segments alternate in direction, the divergence angles caused by successive segments would paint back and forth over the same small range so that the net divergence added to the completely stripped beam would be relatively small. This is shown schematically in Figure 3.

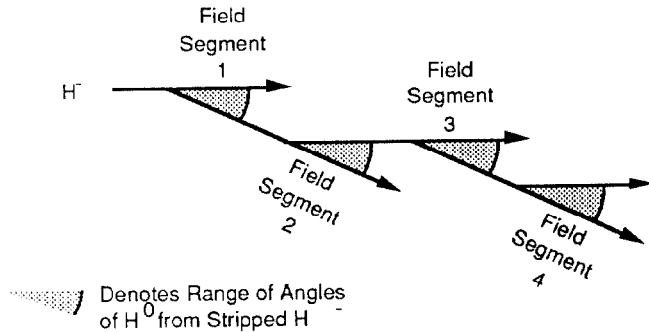Denotes Range of Angles of H^0 from Stripped H^-

Figure 3. Illustration of the Range of Deflection Angles Contributed by Each of Four Field Segments in a Wiggler-Magnet H^- Stripper (The contributions from all segments overlap the same range of angles).

From this figure it is evident that here would be an increase in transverse beam size and a resulting emittance increase. However, in the case of stripping of the H^- beam for injection into the PSR, this effect is small compared to the effect of divergence growth.

III. THEORY

A. H^- Lifetime and Stripping Rate

If $\tau(z)$ is the H^- ion rest-frame lifetime for stripping to H^0 in a field of $B(z)$ Tesla, where z is the H^- position along the beam direction, then the fraction of the original number of number of ions stripped per unit path length travelled can be expressed [1] as

$$\frac{df}{dz} = -\frac{f(z)}{\beta\gamma c\tau(z)} \quad m^{-1} \quad (1)$$

where β and γ, the relativistic β and γ, are 0.841 and 1.848 respectively for 800-MeV H^- ions, and c is the speed of light. The rest-frame lifetime has been expressed by Scherk [2] as

$$\tau(z) = \left[\frac{A1}{E(z)}\right] \exp\left[\frac{A2}{E(z)}\right] \quad sec \quad (2)$$

where $A_1 = 2.47 \times 10^{-6}$ V-s/m, $A_2 = 4.49 \times 10^9$ V/m, and E(z), the ion rest-frame transverse electric field, is given by

$$E(z) = \beta\gamma cB(z) \quad V/m \quad (3).$$

B. Angular Divergence Added by H^- Stripping

For a vertically pointing field, the net horizontal-plane angular deflection of an H^- trajectory after it has travelled from z=0 outside the field region to a point z inside the field can be written as

$$\theta(z) = \int_0^z \frac{B(\xi)}{4.866} d\xi \quad (4)$$

where 4.866 is the beam stiffness (in Tesla-m) of 800–MeV H^- ions, and B is in Tesla.

The quantity of interest at this point is the distribution, at z, of deflection angles for the ensemble of H^0s arising from those H^- ions that have been stripped. If N_0 is defined as the number of H^- ions entering the stripper magnet field, then the deflection distribution can be expressed as

$$\frac{dN}{d\theta} = -N_0 \frac{df}{dz} \times \frac{dz}{d\theta} = -N_0 \frac{df}{dz} \times \frac{1}{\frac{d\theta}{dz}} \quad (5)$$

where $\frac{df}{dz}$ is given by equation (1), and $\frac{d\theta}{dz}$ is obtained by differentiating in equation (4). For the PSR stripper magnet all the beam is stripped in the rapidly rising field at the entrance to the magnet gap. The distribution of deflection angles, $N(\theta)$, is gaussian-like and can be characterized by an rms width, θ_{rms}.

B. Beam Emittance Growth

The emittance, ε, of the H^- beam at the entrance to the stripper magnet can be expressed as $\varepsilon_{in} = \pi \sqrt{\det \sigma_{in}}$ [3] with the sigma matrix being defined as

$$\sigma_{in} = \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix} \quad (6).$$

$\sqrt{\sigma_{11}}$ and $\sqrt{\sigma_{22}}$ are the rms spatial and angular widths in the horizontal plane, and the off-diagonal elements $\sigma_{21} = \sigma_{21}$

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describe the orientation of the beam ellipse in x-θ phase space.

If the rms angular spread of the deflection angles caused by the stripper magnet field is written as θ_{rms}, then the only change in the sigma matrix for the H^0 beam exiting the magnet is in the σ_{22} element. The new element, $\acute{\sigma}_{22}$, is

$$\acute{\sigma}_{22} = \sigma_{22} + \theta_{rms}^2 \qquad (7).$$

For a typical PSR injection line tune, this increase in σ_{22} results in an emittance growth of approximately a factor of three.

IV. CALCULATED DIVERGENCE GROWTH

A. *Present PSR Stripper Magnet*

By substituting known or hypothesized magnetic field distributions into the appropriate expressions in section III, one can then use equation (5) to calculate the distribution of deflection angles of H^0's exiting from a stripper magnet. Such simulations have been done for configurations similar to the PSR stripper magnet and the results agree well with measurements [1]. For the present PSR stripper magnet the predicted rms spread introduced into the beam is 0.37 mrad.

B. *Proposed Wiggler-Magnet Stripper*

In order to illustrate the validity of the wiggler-magnet stripper concept, angular divergence calculations were done for a hypothetical magnet whose field direction alternates through ten cycles of a sine-wave function with cycle length of 1.5 cm, and whose maximum field strength is 1.26 T. With this choice of cycle length and maximum field strength, integration of equation (1) over the full magnet length (twenty half cycles) shows that 99.99% of the incoming H⁻ will be stripped. This high stripping efficiency is essential because any unstripped H⁻ beam is lost in such a way that it contributes to the very beam losses that the use of a wiggler-magnet stripper is meant to reduce.

The angular spread introduced into the beam by a single half–cycle of the magnet described above is described by equation (5), and is calculated to have an rms width of only 0.18 mrad. As was pointed out earlier, since the angular spread from alternate segments of the magnet paint back and forth across each other, the rms spread for one segment applies to the total stripped beam at the end of the magnet. The calculated rms spread of 0.18 mrad is a roughly 50% reduction below the 0.37 mrad rms spread calculated for the present PSR stripper.

V. BEAM-LOSS CALCULATIONS

If the stripper-added beam divergence and the resulting emittance growth were reduced by use of the wiggler-magnet stripper described above, how much would ring beam losses be reduced? To answer this question, a Monte Carlo program was written to simulate beam losses on the limiting apertures in the PSR. One input to the program is the emittance of the injected beam, i.e., the emittance of the H^0 beam as it exits

the stripper magnet. Calculations of beam loss rates for the PSR using the present stripper magnet are within about 20% of the measured values. This result indicates that the Monte Carlo program model used is reasonably accurate. The calculated loss rate with wiggler-magnet stripping is only 45% of the rate calculated for the present stripper magnet. This is a significant reduction; it indicates that, in the absence of other limiting factors, the circulating beam current in the PSR could be doubled without increasing losses above those now observed.

VI. LIMITATIONS OF MAGNET TECHNOLOGY

Until now nothing has been said about the possibility of building a wiggler magnet that would meet the specifications of cycle length and field strength needed in order for it to function as an effective stripper magnet. A brief review of current wiggler magnet technology was done, and the conclusion reached was that, with present state-of-the-art technology, it is probably not feasible to build a magnet with specifications that match those of the hypothetical magnet described in section IV. But, verification of this conclusion would require a systematic study of a range of designs involving consideration of stripping efficiency and divergence growth for different numbers of field cycles, different cycle lengths, and different maximum field strengths.

Permanent magnet wigglers are limited to relatively low field strengths (typically less than a kilogauss) with a resulting low H⁻ stripping efficiency, and are also subject to radiation damage in the high-energy proton and neutron environment near the PSR stripper location. A difficulty with electromagnet construction is in attaining the relatively high maximum field values needed while at the same time spacing the individual magnet segments closely enough together to make cycle lengths near one or two centimeters.

In spite of these limitations on field strength and cycle length, specifications attainable with present technology seem close enough to encourage further study.

VII. REFERENCES

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