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NEUTRAL BEAM INJECTION FOR A PROTON STORAGE RING*

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Abstract

The spallation neutron source at the Los Alamos Scientific Laboratory is to be upgraded with the addition of a high current Proton Storage Ring (PSR). This paper describes a novel charge changing injection technique that substantially simplifies the ring design. The method consists of converting the 800-MeV negative hydrogen (H^-) ion beam from the linac to a 100% neutral hydrogen (H^0) beam having an acceptable emittance and drifting it directly onto the proton closed orbit in the ring. The neutralization is accomplished by electric field dissociation of the H^- ions.

Introduction

The existing Weapons Neutron Research Facility (WNR) at the Los Alamos Scientific Laboratory uses the 800-MeV proton beam from the LAMPF linac to produce neutrons by spallation reactions in heavy metal targets. Because time of flight methods are used to determine the neutron energies, short intense proton beam pulses are required. Although the average beam current from the LAMPF linac is more than adequate, the duty factor and peak current are not ideal for this application.

The Proton Storage Ring[1], which has recently been approved as a major upgrade for the WNR facility, radically inproves this situation. It converts the LAMPF pulse structure into one that is optimized for driving the pulsed neutron source. Basically the PSR accumulates current at moderate intensities from LAMPF for up to 500 μs and then delivers it to the neutron production target in very intense 1 ns long bunches at high frequency (for fast neutron measurements) or 270 ns bunches at low frequency (for thermal neutron experiments.). In both bunch modes the PSR will provide neutron pulse peak intensities unmatched by any other laboratory source in the U.S.

Charge Changing Injection

The key to attaining such very high pulse intensities in the PSR is multiturn charge accumulation while preserving a reasonable stored beam emittance. By "multiturn," we mean several hundred to several thousand continuously injected turns. Conventional proton synchrotrons are loaded by injection from linacs or smaller synchrotrons, stacking the beam bunches in transverse (betatron) phase space or at different energies on successive turns. The number of turns that can be stacked in this fashion is small and is limited by growth of the transverse beam dimensions. This limitation is fundamental and arises from the fact that the stored beam phase space density (brightness) cannot exceed that of the injected beam. Liouville's theorem in statistical physics states that in reversible processes like these the hydrodynamic derivative of the physical distribution function is zero. The six-dimensional phase space density described by the distribution function cannot change.

A straightforward way to circumvent Liouville's restriction is to use an irreversible injection scheme. Charge changing injection of protons, first demonstrated at Novosibirsk[2] and now in routine use in the booster synchrotrons at ANL and FNAL, accomplishes this by injecting an H^- beam near the normal closed orbit and stripping off the electrons in a thin foil. The conversion of H^- ions to protons is an irreversible process and Liouville's constraints therefore do not apply. In fact, protons can be continuously injected into the same phase space and the beam brightness increased to very high levels in comparison with that of the injected beam. The phase-space densities that can be reached are limited only by space-charge considerations (tune shifts) and scattering in the foil, which is a relatively weak process. Charge changing injection is essential to the high current performance goals of the PSR, and also for those of the Spallation Neutron Source at the Rutherford Laboratory (UK) and the proposed IPNS II neutron source at ANL. The brightness of the stored beam must be increased as it is accumulated if the ring apertures are to be kept reasonable and if beam dimensions in the extraction transport system are not to be too large.

Figure 1 is a schematic representation of the charge exchange injection scheme originally proposed for the PSR. The LAMPF H^- beam is inflected onto a distorted closed orbit in a straight section of the PSR lattice by magnet D. Magnets C and E each have integrated field length half that of D and have opposite polarity. A thin stripping foil near the exit plane of magnet D converts the H^- ions to protons.

At ANL and FNAL the injection energy of the H^- ions is relatively low. In contrast, the PSR injection energy is 800 MeV. This beam has a high magnetic rigidity ($B\rho$ = 4.88 T-m); furthermore, the H^- ions must be transported to the injection point in 0.4 T fields to avoid electric field stripping to neutral hydrogen. To maintain 10-fold symmetry in the PSR lattice the length of straight section available for beam injection is restricted to about four meters. The field in magnet D must be held below 0.4 T, and the incoming beam must clear the focussing quadrupole in the injection section. These requirements are difficult to meet in the available space. This scheme furthermore requires a distortion of the normal closed orbit during the injection cycle. The performance requirements of the pulsed magnets needed for this orbit "bump" are severe, 8-kJ stored energy switched at 120 Hz. In addition, these magnets break the symmetry of the lattice and may introduce resonance stopbands which would be absent in a lattice with exact 10-fold symmetry.

Neutral Hydrogen Injection

Most complications in the H^- charge changing injection method can be avoided by using neutral hydrogen injection, as illustrated in Fig. 2. The 800-MeV H^- ion beam from LAMPF is first converted to neutral hydrogen in stripper A and then drifts through bend magnet B and quadrupole Q_f onto the undistorted closed orbit in the straight section. The H^0 beam is there converted to protons by a stripping foil and becomes part of the stored circulating beam. To minimize stored beam interaction with the foil it can be rotated away from its injection position by a spinning disk arrangement such as that formerly used at ANL in the Booster I synchrotron. Programmed steering magnets located in the injection line upstream from the H^- ion stripper will allow the neutral beam to be "painted" across the stripping foil. This technique

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increases the emittance of the stored beam, thereby reducing the incoherent space-charge-induced tune shift for a given number of stored protons.

At low energies, H^0 beams are conventionally formed from H^- ions by stripping in a gas channel. Unfortunately, the cross sections at 800 MeV for conversion of H^- to H^0 and H^0 to H^+ are such that the maximum equilibrium fraction of H^0 is only about half the incident H^- beam, the remaining 50% being divided about equally between H^- and H^+. For PSR injection conditions, this conversion efficiency is much too small. Beam losses would be on the order of 50%.

Field Dissociation of H - Ions

Negative hydrogen ions decay to H^0 in strong electric fields by Stark effect removal of the weakly bound second electron. Measurements of the decay rate were made by Stinson et al. as a part of the TRIUMF design effort.[3] They found that if the decay rate were described as $1/\tau = (E/A_1)\exp(-A_2/E)$, where E is the electric field, then $A_1 = 9.6 \times 10^{-6}$ s V/m and $A_2 = 4.256 \times 10^{-9}$ V/m. Electric fields to provide significant stripping rates are very high ($\sim 10^8$ V/m). However, such fields are readily obtained in the center-of-mass frame of 800-MeV H^- ions by applying a transverse magnetic field of > 0.4 Tesla in the laboratory frame. Figure 3 plots the path length required for an 800-MeV H^- ion beam to decay to 1/e of its initial intensity as a function of the applied magnetic field. The data of Stinson et al.[3] on which this calculation is based correspond to relatively long lifetimes. The PSR magnetic stripper will have to operate in a region of much shorter lifetimes (10^{-10} s rather than 10^{-5} s) and much higher fields. To determine high field lifetimes more accurately than can be expected from an extrapolation of the data in Fig. 3, an experiment to measure stripping rates in 15-20 kG fields is being prepared.

The stripping rate in a practical magnetic field can be calculated using the results of Stinson et al.[3] In the ion rest frame $E = \gamma\beta cB$ where B is the component of magnetic field transverse to the beam in the laboratory frame. It is convenient to express the ion lifetime as a distance $s_0 = v\tau = \beta c\tau$. Thus

$$s_0(s) = (A_1/B)\exp A_2/\gamma\beta cB(s) \qquad (1)$$

where s is the longitudinal coordinate of the ion trajectory.

If f(s) is the fraction of the H^- beam which has not been stripped (f (source) = 1), then $df(s)/ds = f(s)/s_0(s)$

and

$$f(s) = \exp\left[-\int_{\text{source}}^{s} \frac{ds'}{s_0(s')}\right] \qquad (2)$$

This can be integrated numerically to find f(s) and df(s)/ds, the local rate of neutral beam production. Figure 4 is a plot of these functions for an optimized but practically realizable transverse magnetic field B(s), shown in Fig. 6. To minimize the angular dispersion inherent in the stripping process, it is desirable to produce as steep a field gradient as possible. It is apparent from the figures that essentially all of the stripping occurs in a path length interval of ~5 mm, where the magnetic field rises from 0.4 to 1.75 T. The integral of the bending angle $d\theta$ over the baseline width of the df(s)/ds profile is a measure of the angular spread of the neutral beam produced by the stripping process. For the given field profile this is about one milliradian. A larger magnetic field gradient dB/ds near B = 1.5 T would give a smaller angular dispersion, as would a higher peak field.

The emittance increase of the circulating beam in the PSR that arises from the neutral injection process can be minimized by four procedures:

1. using the highest practical field gradient in the stripping magnet;
2. placing the stripping magnet as close to the stripping foil as is practical;
3. designing the injection transport line to locate a beam waist at the stripping magnet in the plane transverse to the magnetic field direction (in the dispersion plane); and
4. using as thin a stripping foil as is practical.

The second of these points follows from the fact that the neutral beam cannot be focussed. The third point, strictly true only if the magnetic and foil strippers are close together, arises from the fact that emittance growth during neutralization is caused by an accompanying fractional increase in beam angular spread relative to the initial angular spread. The purpose of using a thin foil for the $H \to H^+$ process is to minimize small-angle Coulomb scattering.

Halbach has suggested[4] a magnet design for the $H^- \to H^0$ stripper, which is shown in section in Fig. 5. The H^- beam first drifts through a (reversed) magnetic field of -0.5 T between the pole faces AA', where no significant stripping occurs. It then passes through a region between pole faces AA' and CC' and then between pole faces CC' where the magnetic field reaches 1.75T. Most of the stripping occurs in the high gradient region near 1.75T. A magnetic field profile for this magnet obtained by conformal mapping is shown in Fig. 6. The advantage of this design is that the field gradient is greater than that attainable by magnet CC' alone or by magnet CC' passively field clamped.

Conclusions

Neutral beam charge changing injection appears to be a simple method of circumventing the Liouville theorem, avoiding many of the engineering complications of the older, direct H^- stripping method. Additionally, it does not require the use of magnets to distort the normal closed orbit, which necessarily break the lattice symmetry. Although the application of this method in the PSR is made particularly attractive by the high injection beam energy, modern wiggler magnet technology permits using it at lower injection energies. The angular spread induced in the beam would then be that cause by a single period of the wiggler field.

References

1. R. K. Cooper and G. P. Lawrence, Proceedings of the 1977 Particle Accelerator Conference, Trans IEEE NS-24, 1037 (1977).
2. G. I. Budker, Proceedings of the V International Conference on High Energy Accelerators (Frascati, 1965), p. 389.
3. G. M. Stinson et al., Nucl. Instr. and Meth. 74, p. 333 (1969).
4. K. Halbach, Lawrence Berkeley Laboratory, Berkeley, CA, private communication (1979).

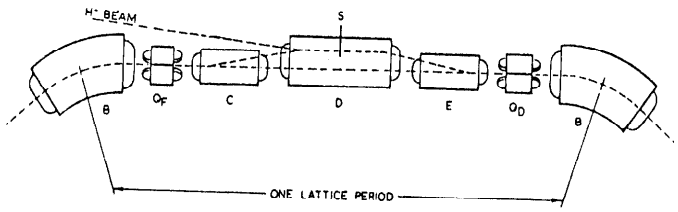

Fig. 1. Conventional charge changing injection for the PSR. Components are described in text.

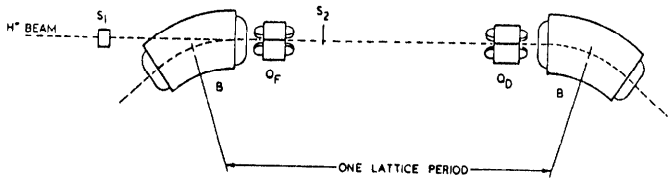

Fig. 2. Two step charge changing injection for the PSR. Components are described in text.

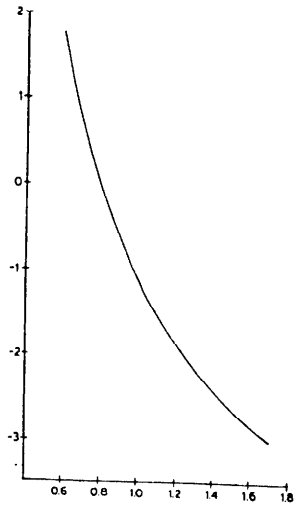

Fig. 3. Logarithm of mean stripping length S_0 (in meters) as function of transverse magnetic field B (in Tesla) for 800 MeV H^- ions.

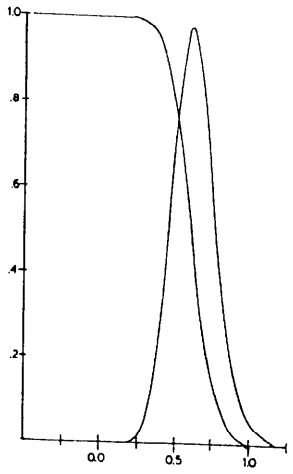

Fig. 4. Fraction F(s) of unstripped 800 MeV H^- ions and local charge stripping rate -dF/ds (scaled by factor of 3.3 mm) as function of position for magnetic field of Fig. 6.

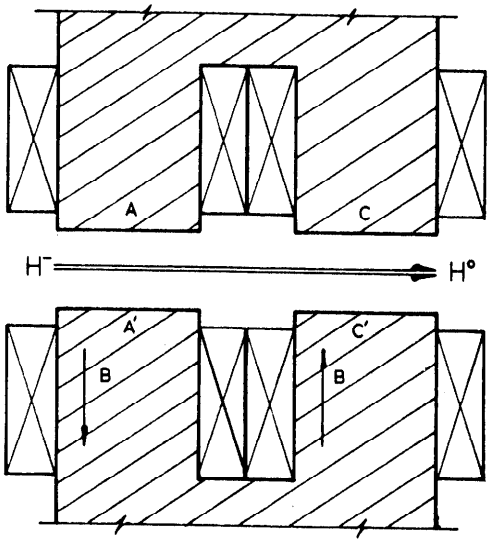

Fig. 5. Magnet design suggested by K. Halbach to produce field of Fig. 6.

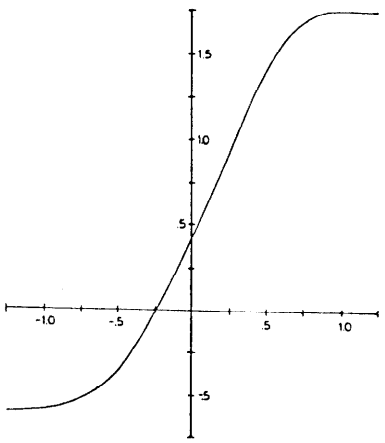

Fig. 6. Magnetic field of magnet of Fig. 5, obtained by conformal mapping.