IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

NEUTRALIZATION OF H^- BEAMS BY MAGNETIC STRIPPING*

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Summary

The stability of H^- beams passing through strong magnetic fields has been relevant to accelerator transport problems and, recently, to neutral beam preparation techniques. We have measured the H^- electron detachment rate as a function of rest-frame electric field and provide parameters for a theoretical lifetime expression. We discuss the limitations imposed on H^- transport by magnetic stripping, and neutral-beam preparation in emittance growth, magnetic fields, and beam energies. Application techniques are also briefly discussed.

Introduction

An H^- ion beam passing through a transverse magnetic field $\underline{B}$ with velocity $\underline{\beta}c$ is subject to a rest-frame electric field $\underline{E} = \gamma c \underline{\beta} \times \underline{B}$. This electric field gives rise to a finite ion lifetime because of the field-induced ion-continuum degeneracy and consequent field dissociation. For ions with energies of hundreds of MeV, the $H^- \rightarrow H^0 + e^-$ dissociation rate can be significant in magnetic fields of the magnitude used for beam transport. This same effect can be put to practical use for neutral-beam preparation.[1,2]

Stripping Rate

In a recent experiment at LAMPF the electric field dissociation rate was measured over five decades of ion lifetime.[3]

An 800-MeV H^- beam from the LAMPF linac was well collimated and attenuated to countable levels ($\sim 10^4\ s^{-1}$) by apertures and thin foils. It then was passed through a special magnet with a region of linearly increasing field, a short constant-field region, and a region where the field decreased rapidly to zero. The magnet could be oriented so that either the linearly increasing or the steeply increasing field was first encountered by the beam. Ions were deflected by the magnetic field until stripped to neutrals. Thus the spectrum of angular deflections could be measured and analyzed to determine the stripping rate. Angular deflections were determined after passing through a 5-m drift space with a multiwire proportional chamber. A scintillation counter telescope and appropriate spatial and temporal cuts of the data were used to improve the signal-to-noise ratios.

The results of the LAMPF experiment span the range from 3 ps to 3 μs. Combined with the results of G. Stinson, et al.,[4] the data span the range from 3 ps to 100 μs. L. Scherk[5] has expressed the rest-frame lifetime τ of the H^- ion as

$$\tau = (A_1/E)\exp(A_2/E) \quad , \qquad (1)$$

where $E = \gamma\beta c B$ is the ion rest-frame transverse electric field. Experimental results fit this form well; for the combined data sets,
$A_1 = 2.47\ 10^{-6}$ V•s/m (±4%)
$A_2 = 4.49\ 10^{9}$ V/m (±0.25%).

Beam Transport

It has long been recognized that the field stripping of ions sets practical limits on the magnetic fields used for beam transport of H^- ions. The dissociation-rate measurements of Stinson et al.[3] were made as part of the TRIUMF H^- ion cyclotron design effort. The LAMPF measurement[2] extends the data to rates that were previously unmeasured and confirms the theoretical form predicted by Scherk.[4]

Loss rates in H^- beam-transport lines can be expressed as the fraction of the ion beam neutralized when passing through a length in a specified transverse magnetic field. If the ion mean lifetime is given by Eq. (1), then the fractional loss rate is given by

$$\frac{df}{ds} = -f/(\beta\gamma c\tau) = (fB/A_1)\exp[-A_2/(\beta\gamma cB)] \quad , \qquad (2)$$

where f is the unneutralized fraction of the original ion beam and s is the longitudinal coordinate along the beam. The quantity $\beta\gamma c\tau$ then represents a stripping length. Figure 1 is a plot of contours of constant loss rate, as a function of ion kinetic energy and bending radius. The figure shows that energetic H^- ion accelerators require large bending radii in their transport lines to avoid H^- stripping spills.

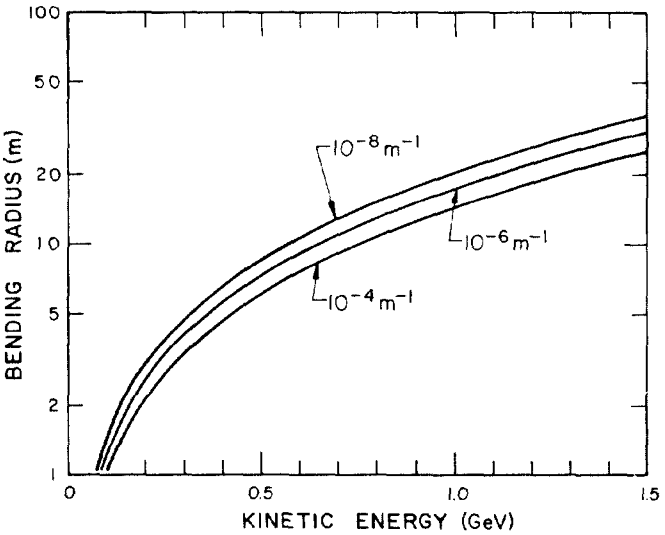

Fig. 1. Beam-neutralization rate isocontours, as a function of H^- ion kinetic energy and bending radius. Contours are for fractional loss rates of $10^{-8} m^{-1}$, $10^{-6} m^{-1}$, and $10^{-4} m^{-1}$.

Neutral-Beam Preparation

Stripping Criteria

The LAMPF H^- stripping-rate measurements[2] were motivated in part by the desire to prepare an 800-MeV neutral hydrogen beam with acceptable emittance increase, caused by the stripping process. Such a beam could be injected into the 800-MeV proton

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*Work performed under the auspices of the US Department of Energy.

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accumulator ring, now under construction at the Los Alamos National Laboratory, by drifting it through bending and focusing magnets in the ring lattice.[1] This injection method would avoid the substantial ion optical engineering problems associated with the application of a single-step, charge-changing injection method at 800 MeV.

Because of the distribution in the locus of neutralization implied by Eq. (2), an angular spread, as well as a net angular deflection, is induced in the stripped beam. *In general*, a practical stripper magnet will be designed to accomplish virtually complete stripping in the magnet fringe field. A sufficient criterion for such stripping by a magnet with asymptotic peak field B_0 and maximum fringe gradient B'_m is given by

$$\beta\gamma c\tau_0 << B_0/B'_m \quad , \tag{3}$$

with τ_0 evaluated from Eq. (1) at $B = B_0$. Adequate or necessary conditions depend on the field configuration and may be evaluated by numerical integration of Eq. (2). Assuming complete ionization in the magnet fringe, the angular growth is a monotonically decreasing function of the field gradient at which detachment occurs. Neutralization in a linearly increasing field results in an angular distribution, which is closely approximated by a Gaussian distribution with rms angular width σ_0 which decreases with the field gradient B'. This dependence is shown in Fig. 2 as contours of constant rms angular spread for a beam with negligible initial divergence, in a plot of kinetic energy versus inverse field gradient. The energy range spanned by the plot provides approximate limits for which the beam-neutralization technique can be applied. At higher energies, beam transport without substantial detachment losses becomes difficult; at the lower range of energies, reasonable beam divergences are not achievable with practically realizable fields and gradients. Figure 2 shows also the contours of field B_s at which the peak in the angular distribution originates.

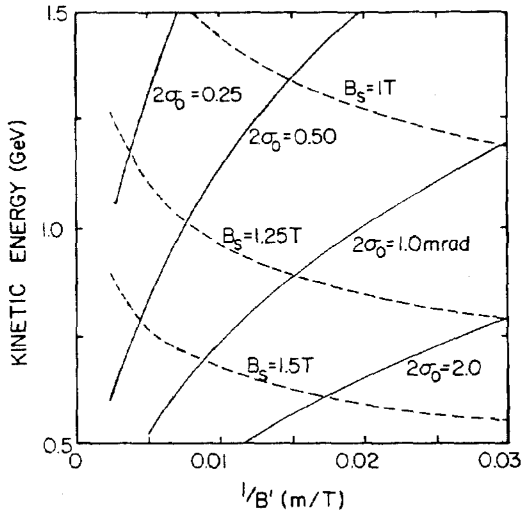

Fig. 2. Isocontours of angular width $2\sigma_0$, and magnetic field B_s, corresponding to peak rate in angular distribution as a function of beam energy and inverse gradient for a stripping field with constant gradient B'.

Stripper-Magnet Design

A possible stripper-magnet configuration is suggested in the inset of Fig. 3; a second set of (unenergized) pole pieces with the same gap G as the high-field dipole is positioned at a distance D from the magnet. Field solutions obtained by conformal mapping (assuming infinitely permeable pole-piece material) are shown in Fig. 3 for three values of D/G. The maximum field gradient along the midplane axis is given by

$$B'_m = \frac{B_0\pi}{2G} \tag{4}$$

at a field $B_0/2$ for $D = 0$. As D is increased to G, B'_m decreases by a factor of 0.62 at 0.61 B_0. For the limiting case of large D (that is, a dipole magnet), B'_m is reduced by a factor of two from Eq. (4) at 0.70 B_0. In practical magnets, these figures are approximately valid if fields and materials are such that the relative permeability in all parts of the magnet are sufficiently high. The gradients may be enhanced in this configuration by energizing the neutral poles in the direction opposite B_0.

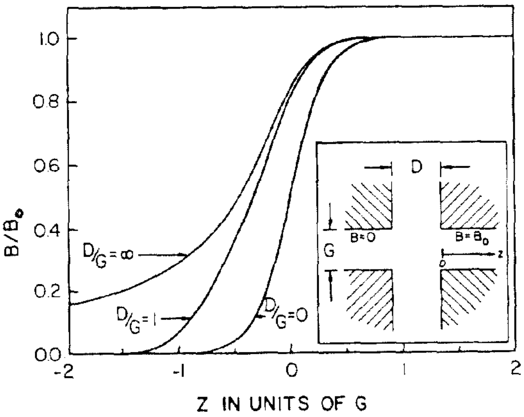

Fig. 3. Analytical results for axial field of magnet shown in inset, with right-hand pole pieces energized to an asymptotic field B_0.

Angular Distribution and Beam Emittance

An example of an angular distribution is given in Fig. 4 for a perfectly collimated 800-MeV H^- beam

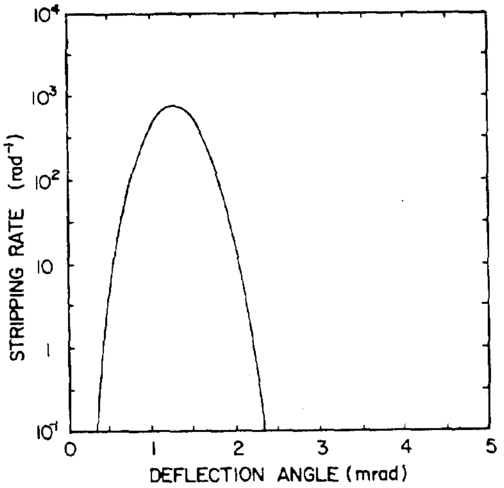

Fig. 4. Angular distribution of a perfectly collimated 800-MeV ion beam neutralized in the field of Fig. 3 for D = G = 1 cm and $B_0 = 2$ T. The rms width $\sigma_0 = 0.37$ mrad.

passing through an ideal magnet, with $B_0 = 2T$ and $D = G = 1$ cm. Such simulations with similar configurations agree well with experimental results and can be used for magnet design. Alternatively, Fig. 2 presents a guide for field specification. The field extent δB over which the gradient should remain high can be estimated from

$$\delta B = \frac{B'_m B_\rho \sigma_o}{B_s} \quad , \tag{5}$$

where B_ρ is the beam rigidity. Equation (5) gives the extent of field on *either* side of B_s, so that 68% of the particles are stripped in $2\delta B$ centered around B_s.

The ion loss-rate expression, Eq. (2), can be numerically integrated for trajectories through a magnet. Figure 4 shows an angular distribution obtained by this method for a beam with initial zero divergence. Such calculations agree well with experimentally observed distributions and can be closely fitted to Gaussian forms. This form permits determination of beam emittance growth in analogy to incoherent thin-target scattering. Characterizing an incident beam of arbitrary distribution and finite rms emittance ε by the usual (rms) transport parameters σ_{11}, σ_{22}, and r_{21}, the angular widths combine quadratically; that is, the post-magnet angular matrix element σ'_{22} is given by

$$\sigma'_{22} = \sigma_{22} + \sigma_o^2 \quad . \tag{6}$$

The ratio of the new emittance ε' to ε can be expressed as

$$\frac{\varepsilon'}{\varepsilon} = \left(1 + \frac{\sigma_{11}\sigma_o^2}{\varepsilon^2}\right)^{1/2} = \left[1 + \frac{\sigma_o^2}{\sigma_{22}(1 - r_{21}^2)}\right]^{1/2} \quad . \tag{7}$$

The two forms of Eq. (7) provide alternate parameterization and are related through the expression for ε in the beam matrix elements. Minimization of the relative emittance growth is obtained for smallest spot size at the stripper magnet.

Beam Manipulation

H^- beams are commonly manipulated by producing H^+ or H^0 beams, using stripping foils. The neutral beams may then be passed through magnets without deflection and stripped by a further foil to H^+. Magnetic stripping presents an alternative to this technique, with virtually 100% efficiency--assuming that the emittance growth in stripping is tolerable. Additionally, magnetic stripping can be done with very small nuclear depolarization (in contrast to foil stripping) and may be particularly useful in polarized beam manipulation.[6] For applications where partial stripping is required or sufficiently high fields are not attainable for fringe field stripping, a wiggler magnet configuration may be used to limit beam angular spread.

Conclusion

High energy H^- ion beams will continue to be used in existing and future accelerators. The H^- ion field-stripping rate is now known over a sufficiently wide range of values to calculate transport-line loss rates with good accuracy. It is also possible to calculate the quality of neutral beam that can be prepared by field stripping of ion beams. This has potential applications for charge-changing beam injection and for sharing beam between several lines.

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