Machine Studies at the Los Alamos Proton Storage Ring*

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Abstract

Results from recent machine development studies at the Los Alamos Proton Storage Ring (PSR) are presented on the origin of the "first-turn" losses, the PSR instability, and volume H^- ion source development. An experiment has been performed to measure the production of excited states of H^0 when 800-MeV H^- ions impinge upon thin (70-300 μg/cm2) carbon foils. Preliminary results indicate yields of about 0.5% each for the n=3 and n=4 states. Much evidence has been accumulated supporting the hypothesis that the PSR instability is caused by coupled e-p oscillations, but a truly definitive and unambiguous test has not yet been performed. Plans for such a test include installation of hardware to suppress the most copious sources of electrons and experiments to measure the quantity of proton beam in the interbunch gap. Good progress is being made to test and evaluate two promising designs for a new high-intensity, high-brightness volume H^- ion source and on fast chopping of the beam by pulsing the plasma electrode.

Introduction

Machine studies and accelerator development efforts at PSR have in the past been focused on increasing the beam intensity, improving beam availability and correcting radiation protection deficiencies. However, during the past year with the prospect that LAMPF might be shut down after October of 1993, the emphasis shifted to studies of issues that are important to the design of a next generation spallation neutron source based on the linac and compressor ring concept. Therefore, the studies of first turn losses (now believed to be caused by the production of excited states of H^0 at the stripper foil[1,2,3] as first proposed by Richard Hutson) and the PSR transverse instability have assumed new urgency.

H^0 Excited States and First-Turn Losses

The losses of 0.2-0.3% on the first turn after injection have long been a puzzle but are now thought to be predominately caused by production of excited states of $H^0(n)$ (with principle quantum number, $n \geq 3$), which subsequently strip part way through the fringe field of the first dipole downstream of the stripper foil and fall outside the acceptance of the ring, as shown schematically in Figures 1 and 2.

In going some distance in the magnet fringe field before being created by stripping, the protons arising from $H^0(n)$ will not be deflected as much as protons that were created at the stripping foil and thus will have an angular displacement with respect to the central trajectory when projected back to the entrance of the magnet. At the PSR, the protons arising from excited states with $n \leq 5$ will have a large enough displacement that many will fall outside of the machine acceptance, as illustrated in Figure 2.

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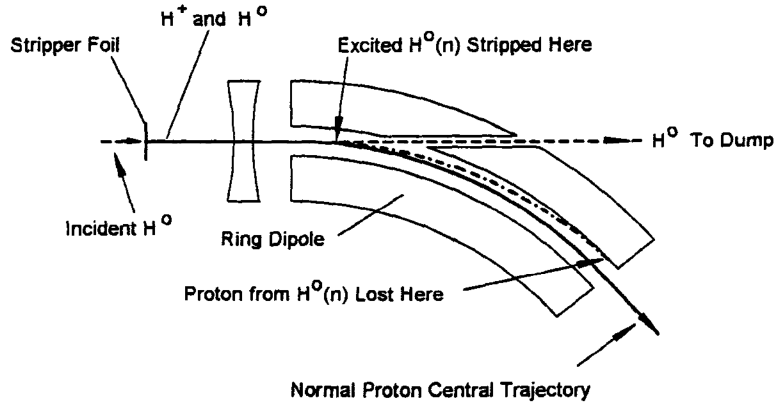

Figure 1. PSR injection region and the origin of "first turn" losses.

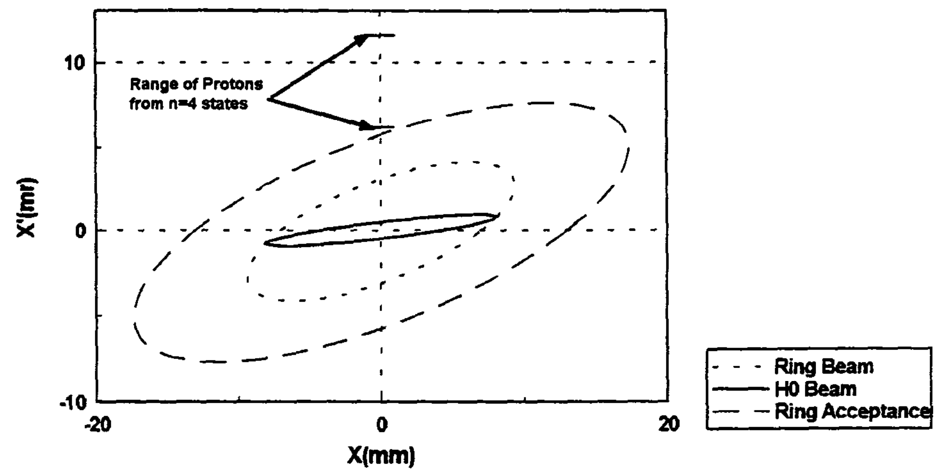

Figure 2. Beam ellipses and the ring acceptance at the entrance of the dipole downstream of the stripper foil. The H^0 ellipse area is four times the rms emittance (2 sigma).

The behavior of excited states of H^0 moving in a magnetic (or in an electric field in the rest frame of the atom) is well understood and can be calculated to good accuracy by a number of methods. For our purpose in tracking lost particles, the fifth-order perturbation theory of Damburg and Kolosov[4] is convenient and sufficiently accurate for calculating the energy and width (lifetime) of any H^0 Stark state as a function of its quantum numbers (the parabolic quantum numbers, n1, n2, and the magnetic quantum number, m), its velocity, and the magnetic field in which it moves. For details on formulas for calculating lifetimes, see references 4 and 5.

The prescription of Damburg and Kolosov to calculate the central energy and width, Γ, of a given parabolic Stark state has been checked against numerical integration of the non-relativistic Schrodinger's equation with essentially no approximations for m=0,1. The agreement[6,7] on central energies is excellent (0.05%) and is better than 20% on the width for lifetimes of interest (1-100 picosecond) here. Furthermore, the perturbation theory results are in good agreement with laser experiments[8] at LAMPF on the hydrogen Stark effect.

The probability, P(z), for $H^0(n)$ to survive to a point located at coordinate, z, in the fringe field of the magnet is given by solution of the basic loss rate equation

$$\frac{dP(z)}{dz} = -\frac{P(z)}{\tau(z)\beta\gamma c} = -\frac{P(z)\Gamma(z)}{\hbar\beta\gamma c}; \quad \text{with solution } P(z) = \exp\left(-\frac{1}{\hbar\beta\gamma c}\int_{-\infty}^{z}\Gamma(s)ds\right).$$

Table I below summarizes results of calculations using the prescription described above along with the measured fringe field profile to compute the distribution of the angular displacement for protons from the field stripping of various excited states. The table also indicates location of proton loss and estimates of yield, which are taken as one-half of the measured yields (in an experiment described below) from H^- incident on the foil. It is plausible to assume that the yield of $H^0(n)$ from incident H^0 beams will be about half that for H^- beams since there are half as many "convoy" electrons traveling with the proton as they emerge from the foil where the proton can recapture an electron to form $H^0(n)$.

Table 1. $H^0(n)$ loss estimates

n	$\Delta\theta$ range (mradians)	Loss Location in the ring	Estimated Yield from 200-$\mu g/cm^2$ foil
3	22 - 50	in the first dipole	0.30%
4	6.1 - 12	after the first dipole but in the next 3 ring sections	0.20%
5	1.8 - 4.4	small fraction lost on the ring limiting apertures	0.15%

While theory provides a good prescription for the field stripping of excited states, at this time only experiments provide information on yields of various excited states from relativistic beams traversing thin foils. Fortunately, we were able to rapidly mount an exploratory experiment to measure the yields of excited states of H^0 produced when 800-MeV H^- ions impinge on thin carbons foils by using existing equipment and expertise provided by our collaborators from the University of New Mexico atomic physics research group, who have been conducting accelerator-based research using laser-ion colliding-beam experiments at LAMPF for the past twenty years.

The experiment layout is shown in the schematic of Figure 3. The main apparatus consisted of the foil box, the gradient magnet, a 5.27-m flight path and a detector system made up a scintillator telescope, a multi-wire proportional chamber, and a scanning scintillator. The scintillator telescope covered the entire beam so that the measurements could be normalized to the total beam. Standard beam diagnostics and phase-space tailoring equipment are not shown.

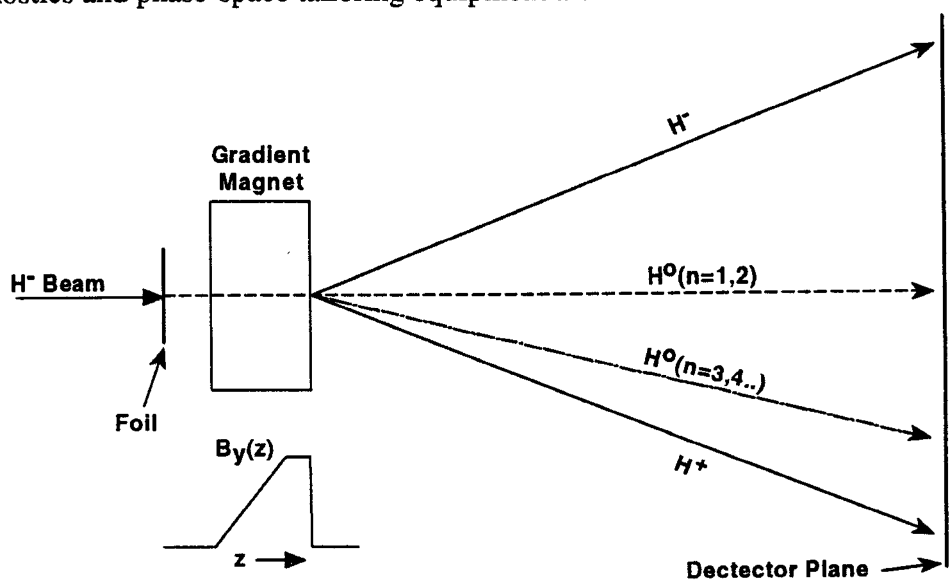

Figure 3. Schematic layout of the experiment to measure the production of excited states.

The gradient magnet is a half quadrupole turned sideways to the beam that enters through a hole in the return yoke and then encounters a vertical magnetic field whose strength increases linearly with distance. A maximum field of 1.9 T is available and the length of the gradient region is 0.20 m

When a given H^0 Stark state reaches a field in the gradient magnet where it has a high probability to ionize, it is stripped and the resulting H^+ is deflected in traversing the remaining downstream magnetic field. By measuring the position where the proton strikes the detector and using the field map of the magnet, one can reconstruct the value of the magnetic field where the proton was produced by stripping.

When the magnet is set to ionize a particular low-lying n-value manifold (n=3,4,5 or perhaps 6) in the linear gradient region of the magnet, each individual Stark state strips over a narrow range of field values that produce a peak separate from most of other substates, except for nearest neighbors and in some cases next-nearest neighbors. This offers the possibility that information on the distribution of substates within a given n-value manifold can be extracted from experimental data. We are in the process of analyzing the data to find the best-fit distribution of substates in the n=3 and n=4 manifolds.

A typical data set is shown in Figure 4 for the magnet set at 1.3 T and for foils of thickness 70 and 200 $\mu g/cm^2$. We are now persuaded that the sharp peak near x=17 cm is spurious (due to scattering from the scanning scintillator supporting plate) and not an excited state of H^0. Data are also available for a 300-$\mu g/cm^2$ -thick foil but are not plotted in Figure 4 to avoid obscuring the main features of the data from the other two foils.

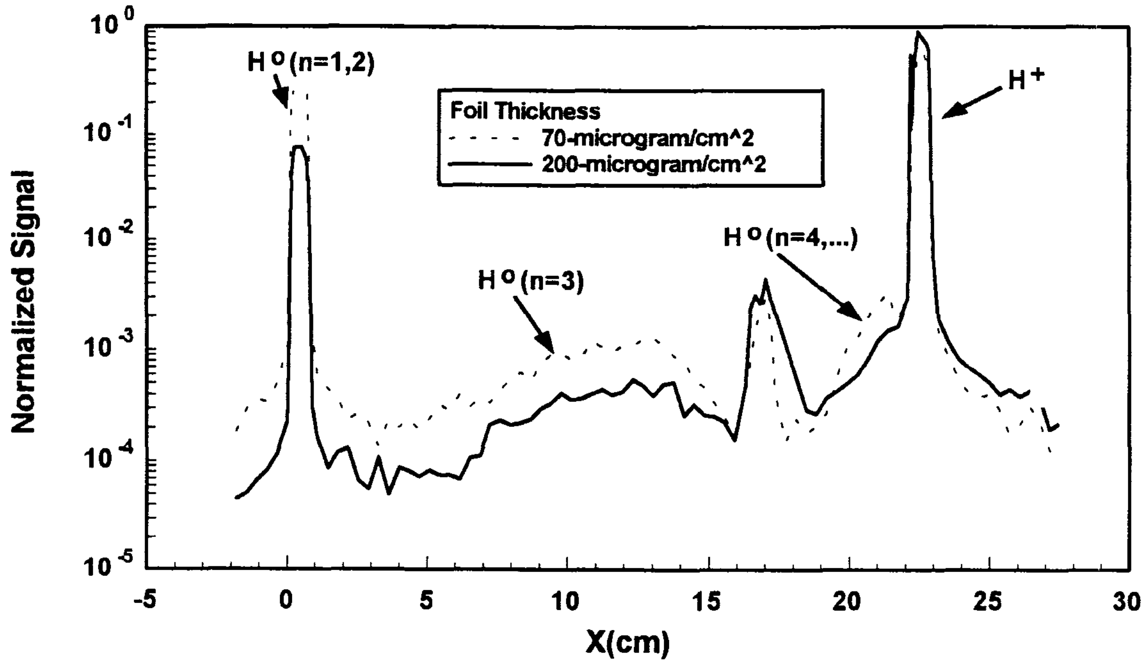

Figure 4. Scanning scintillator spectra for a peak field of 1.3 T.

In the spectra of Figure 4, the n=3 collection of states are separated from the n=1,2 group, as well as from the states n=4 and above. The n=3 collection can be summed to obtain the yield as a fraction of the incoming H^- and as a function of foil thickness. We also have data sets for n=4 collected at a peak field of 0.7 T. The preliminary results of the yield for n=3 states and the sum of n=1 and 2 are tabulated below and plotted in Figures 5a and 5b, along with curves (solid lines) that fit the shape of relative yield data published in reference 5. The curves of Figure 5 were obtained from the following formula which was derived for a simple model, assuming a series of interactions with individual (isolated) foil atoms.

$$Y(x) = N_i \cdot \frac{a}{a+b-c}\left[\exp(-c \cdot x) - \exp(-(a+b)\cdot x)\right].$$

The parameters a, b, and c are taken from reference 5 (a = 0.123, b = 0.00086, c = 0.0131 for n=3 and a = 0.0388, b = 0.00949, c = 0.0109 for n=1) with the overall normalization, N_i, adjusted for a good fit to the data from our experiment. The dependence of relative yield on foil thickness for our data are in good agreement with the curves of reference 5 as is evident in Figures 5a and 5b.

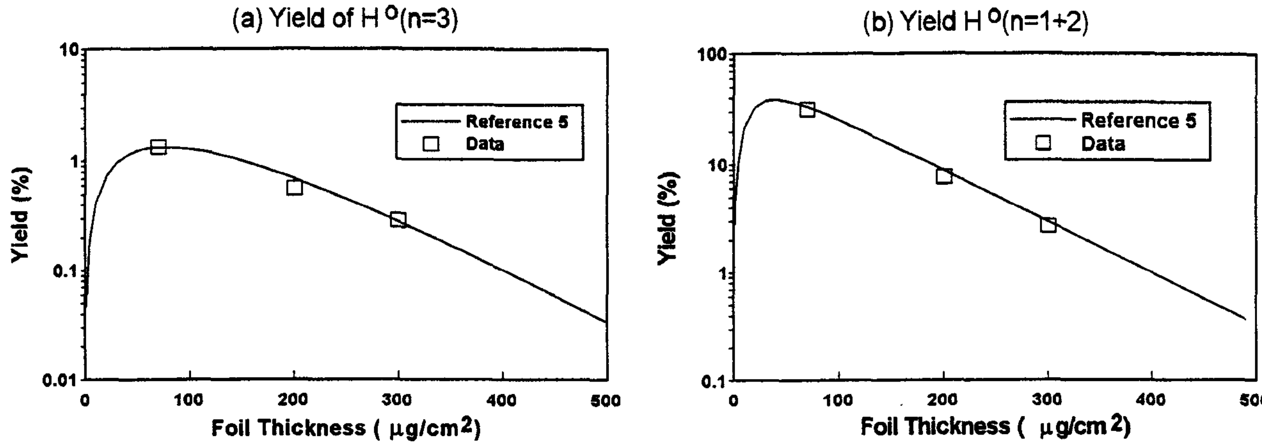

Figure 5. Yields of $H^o(n)$ as a function of foil thickness.

Yield data for the data set taken at 1.3-T peak field.

Foil thickness ($\mu g/cm^2$)	% yield for n=1+n=2	% yield for n=3
70	35	1.34
200	7.5	0.57
300	2.7	0.29

At this time, the best estimates of the percentage yield for other values of n in the range 2-5 are obtained by extrapolation from our results for n=3 using the power law distribution for n reported in reference 5. For a 200 $\mu g/cm^2$ carbon foil this implies $Y(n) = 0.0057(3/n)^{1.3}$.

Another experimental run to refine the measurements made in 1992, to measure yields for more n values and to study the effect of other foil parameters on yields is planned for September, 1993. It would be desirable to study other factors that might affect yields of excited states such as beam energy, the effect of other foil materials (Al_2O_3, Si...), the presence of a magnetic field at the stripper foil, the angle of foil with respect to the beam, and multiple, closely-spaced foils. However, the limited amount of beam time available for the study will restrict the number of factors that can be explored in the next run.

We are convinced that the excited states of H^o produced at the stripper foil are responsible for most of the first-turn losses. All of the available evidence is consistent with this explanation, including the location of the losses, the magnitude of the losses, and the behavior with foil thickness. An alternative explanation, halos on the incoming H^o beam, could explain some but not all of the evidence. It would take an unusual distribution of halo to spill at the observed locations of first-turn losses rather than at the limiting aperture (extraction septum). Most convincing is the reduction in first-turn losses with foil thickness. It is very difficult to see how the first-turn losses from beam halos would be reduced by the observed factor of two for a 300-$\mu g/cm^2$ foil of the same size placed at the same location as a 200-$\mu g/cm^2$ foil. If beam halos were the correct explanation, one would expect the first-turn losses (as a fraction of the H^+ beam) to remain the same.

The mechanism described above for the first-turn losses at PSR will generate some beam halo and possibly some losses for any machine employing charge exchange injection with a H^- or H^o beam incident on a stripper foil. Unless the foil is very thick, some H^o will emerge from the foil and will be separated from H^+ in a magnetic field. The halo can be minimized but not eliminated in its entirety.

The PSR Instability

A strong, fast, transverse instability with high beam loss has long been observed at the PSR above a threshold of ~ $6x10^{12}$ protons per pulse (ppp) in a coasting beam and ~ $3\text{-}3.5x10^{13}$ ppp for bunched beam conditions (12 kV on buncher)[9]. Transverse oscillations of the beam centroid at ~ 100 MHz are observed on stripline beam position monitor (BPM) pickups and increase exponentially with growth times of 10-50 μs for unstable beams at PSR.

Much evidence[10] has been accumulated indicating that the instability is driven by electrons trapped within the proton beam (referred to as the e-p instability seen in certain other proton machines). Plenty of electrons (shown below in the table of known sources of electrons at PSR) are available to provide neutralization at the 1-2 % level, which theoretical studies[10] and simulations[11] indicate is needed for the e-p instability. These studies[10] also show that a small amount of proton beam leakage into the inter bunch gap will cause trapping of electrons over successive passages of the beam bunch, although recent work[11] indicates that the instability may still occur (at perhaps a somewhat higher threshold) with a clean gap if the beam is sufficiently neutralized (a few percent) by fresh electrons created each turn.

Table 2. Known sources of electrons at PSR

Source	Electrons/accumulated proton
1. Electrons (400 keV) stripped from H^0 at the stripper foil	1 + secondaries
2. Secondary emission from stripper foil	5-10
3. Thermionic emission from stripper foil	< 0.1?
4. Secondary emission from beam spill on vacuum envelope	<0.1?
5. Residual gas ionization	~0.05
Total	**6-10 e/p**

Theory suggests that control of an e-p instability should be possible by suppressing the generation and/or trapping of electrons. Electron neutralization of the beam can be suppressed by various electron clearing fields. Leakage of protons into the interbunch gap and the resulting electron trapping can be suppressed by more effective RF bunching of the beam, say, by stronger RF fields at the buncher, a second buncher, or some form of barrier bucket. Since increasing buncher performance is not easily accomplished at PSR and since most (99% or more) of the electrons are produced in the injection straight section, we have chosen to focus on methods to suppress the electrons produced in the injection region.

The layout and configuration of electron collection devices recently installed in the injection straight section are shown in Figure 6. Collecting electrodes fill much of the space. The stripper foil

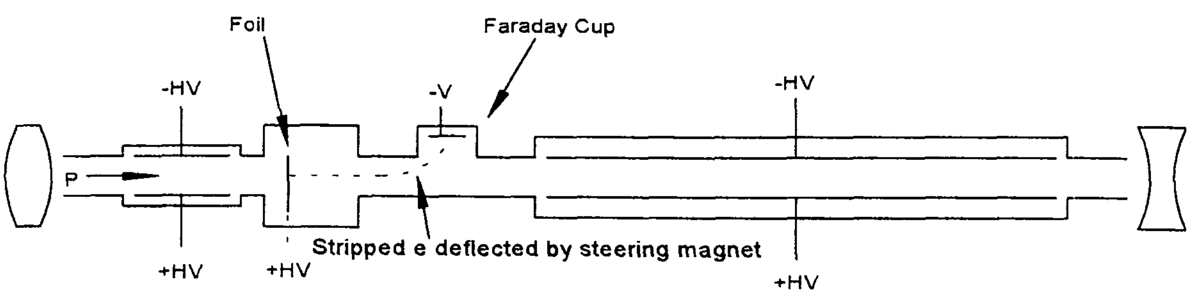

Figure 6. Layout of electron collection devices in the injection straight section of PSR.

can now be biased to ~ 10 kV to suppress secondary and thermionic emission from the foil. A small magnet will deflect the 400 keV electrons (stripped from the incoming H^0 at the stripper foil) onto a biased Faraday cup where they should be collected. Many of the more energetic delta rays from the foil will also be deflected to the Faraday cup. Studies of the efficacy of the newly installed devices will be undertaken in the summer of 1993.

Proton beam leakage at the 1% level into the inter bunch gap is not easily discerned with the existing beam diagnostics. A special beam current transformer with low undershoot is being developed for the 1993 instability studies. It will be placed in the extraction line for measurement of beam in the gap when the extraction kickers are timed to fully extract the gap region. Under these circumstances, beam will show up in the extraction line on either side of the "gap" with ~ 10% of the beam ahead of the "gap" and the rest of the beam coming after, as indicated in Figure 7. We expect to be able to detect and measure beam in the gap if it is ≥ 0.1% of the peak.

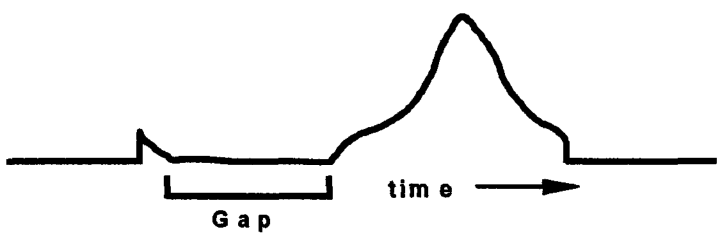

Figure 7. Beam current signal expected from extraction line monitor when "gap" is extracted.

H^- Source Development

Injection of higher peak current into the PSR will reduce the number of turns needed to accumulate a given charge and consequently reduce the number of foil traversals by the stored beam, thus reducing stored-beam losses. Development of a volume H^- source with twice the peak intensity and half the emittance of the present cusp-field source was judged to be feasible and considered to be the most cost-effective next step toward increased intensity. It has the added benefit of reducing the linac duty factor needed to serve the LANSCE program. Such a source would be required for any new spallation source.

A major effort is under way at Los Alamos to test and evaluate two promising options: (a) a dipole-filter design from LBL (Berkeley) and (b) a version of the BNL toroidal-filter volume H^- source engineered for high duty factor operation. Results to date are encouraging and have been reported elsewhere[12]. Both options show the potential to meet the goals discussed above. These studies will also include the use of RF to excite the source plasma for the dipole-filter source.

Design studies for an advanced spallation neutron source indicate that chopping the beam to provide 100-200-ns gaps before the beam reaches the linac will be difficult. Experiments by R. York[12] show that the beam intensity of the small LBL dipole-filter source can be modulated by biasing the plasma electrode. In tests with an arc current of 150 A, 90% of the extracted beam was suppressed when the plasma electrode was biased at -150 or +40 volts. Further tests were made using a simple modulator to pulse the plasma electrode to -150 volts with a rise time of ~ 100 ns. The time response of the source beam intensity followed the rise time of the modulator and the plasma discharge time of ~100 ns. Future tests with a faster modulator are planned to determine the time response limit of beam-intensity modulation.

Conclusions

Machine studies at PSR are highly relevant to development of the next generation of high-intensity compressor rings. All of the new machines will need to deal with the beam halos and beam losses generated by excited states of H^0 produced at the stripper foil. Brighter, more intense H^- ion sources will be needed. The PSR instability could be a serious limitation if means to control it are not developed. Hopefully, the most important results of our proposed machine experiments will be obtained before PSR closes permanently. However, source development can still proceed without the linac and further studies of the production of excited states of H^0 at 400 MeV might be possible at the Fermilab linac.

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