LINAC-DRIVEN SPALLATION-NEUTRON SOURCE*

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Abstract

Strong interest has arisen in accelerator-driven spallation-neutron sources that surpass existing facilities (such as ISIS at Rutherford or LANSCE at Los Alamos) by more than an order of magnitude in beam power delivered to the spallation target. The approach chosen by Los Alamos (as well as the European Spallation Source) provides the full beam energy by acceleration in a linac as opposed to primary acceleration in a synchrotron or other circular device. Two modes of neutron production are visualized for the source. A short-pulse mode produces 1 MW of beam power (at 60 pps) in pulses, of length less than 1 ms, by compression of the linac macropulse through multi-turn injection in an accumulator ring. A long-pulse mode produces a similar beam power with 1-ms-long pulses directly applied to a target. This latter mode rivals the performance of existing reactor facilities to very low neutron energies. Combination with the short-pulse mode addresses virtually all applications.

I. INTRODUCTION

Several high-intensity spallation-neutron sources exist throughout the world. These sources are in general driven by very short (< 1 µs) and intense proton pulses. The ISIS facility [1] at Rutherford Appleton Laboratory operationally delivers an average 160 kW of beam power to a spallation target at an energy of 800 MeV. The rate of pulse arrival is 50 Hz with each pulse containing 2.5 x 10^{13} particles. The LANSCE facility at Los Alamos [2] provides 60 kW at 20 Hz and 800 MeV with 2.9 x 10^{13} particles per pulse. Two other pulsed sources produce lower beam powers; IPNS at Argonne National Laboratory and KENS at KEK Japan produce 7-kW and 2-kW average beam power, respectively.

Both the ISIS and LANSCE facilities utilize a ring to compress a nominally 1-ms linac pulse to less than a microsecond. LANSCE injects into the ring at full energy, using an rf cavity to maintain bunching, while ISIS injects at 70 MeV with subsequent acceleration by rf cavities in the synchrotron ring. The two facilities have similar problems in providing an intense beam (some 15-mA peak current from the source) via a linac for rapid ring filling. However, the LANSCE higher injection energy results in qualitatively different problems and ring behavior [3]. In more recent studies even higher-power beams are proposed for injection into a ring and high-power sources directly driven by a linac are considered. A brief description of such studies and the major problems encountered form the discussion of this paper.

II. THE BASIS FOR RECENT STUDIES

Interest in neutron sources of higher intensity has recently surfaced. In the fall of 1992 a Department of Energy panel noted that the U. S. critically needed new neutron-research facilities. It recommended that the Advanced Neutron Source (ANS), a 330-MW reactor then under study at Oak Ridge, be constructed and a study be undertaken for a 1-MW spallation source producing a short pulse (an SPSS) of less than 1 microsecond. The two types of sources would be complementary and would span the range of desired applications. In general, an SPSS produces higher-energy neutrons and is superior for high-momentum-transfer applications, while a reactor is most useful at low-momentum transfer. There is, however, considerable overlap in the applications at intermediate neutron energies and momentum transfers.

A site-independent study for the SPSS was proposed by the panel, but has not yet occurred. However, Los Alamos, Brookhaven, and Argonne National Laboratories each undertook an informal study considering the feasibility of a 1- to 5-MW SPSS facility at their respective institutions. The Brookhaven and Argonne studies proposed a synchrotron-driven source, while Los Alamos primarily considered an accumulator ring, i. e., a ring injected by a linac at the full spallation energy of 800 MeV, called LANSCE II. In particular, the design attempts to utilize the LAMPF linac and other existing institutional infrastructure.

On a similar time frame, the European Community had begun informal studies of a 5-MW SPSS, known as the European Spallation Source (ESS). The effort has developed into a formal study with respective responsibilities for the linac, ring, and target at the University of Frankfurt, Rutherford Appleton Laboratory, and KFA Jülich. Like LANSCE II, an accumulator ring scheme (at 1.3 GeV and with two rings) has become the primary focus. Other studies, such as the AUSTRON synchrotron have since emerged. These pulsed sources complement the 57-MW ILL reactor at Grenoble, France. It is worth noting that a dc cyclotron-driven 1-MW spallation source has been constructed at PSI in Switzerland.

Recently, it has become evident that the ANS reactor will not soon be constructed. Hence, recent work at Los Alamos has explored the possibility of a long-pulse spallation source (LPSS) that can provide a similar complementarity to a short-pulse source as does a reactor. In this mode, very intense linac pulses, under a millisecond in length, are impinged on a spallation target that has optimized geometry and material content to exploit the pulse time structure. While a precise equivalence between an LPSS and a reactor is difficult to state and depends on the application, an approximate figure for the neutron-source brightness has been determined [4]. This

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result places a 1-MW spallation source in equivalence to a 15-MW reactor in average neutron brightness at the respective moderator output surfaces. The general utilization of this pulsed beam requires time-of-flight techniques using mechanical choppers to energy select neutron energies. From the kinetics of the energy-selection process, a further equivalence can be derived [5] that increases the effective power of the LPSS by the inverse duty factor. Hence for a 60-Hz 1-ms pulsed structure, the effective reactor power of a 1-MW LPSS is 250 MW. The validity of this figure varies widely with application.

III. A LINAC-DRIVEN SPSS

Figure 1 shows a schematic overview of the SPSS study results. A principal feature is the retention of the side-coupled-cavity portion of the LAMPF linac (SCL), which constitutes nearly 90% of the present facility and has a proven present capability of 1-MW operation at 800 MeV and at a 120-Hz repetition rate; hence most of the existing LAMPF infrastructure is plausibly retained. The Cockroft-Walton-housed source and 201.25-MHz drift-tube linac (DTL) are replaced by a 402.5-MHz radio-frequency quadrupole (RFQ) and DTL that accelerate 30-mA peak current of H$^-$ ions to 20 MeV. Subsequent acceleration to 100 MeV by an 805-MHz DTL allows injection into the 805-MHz SCL. The change in frequency at 20 MeV permits the future addition of a funnel for possible upgrades in current.

The 1.2-ms macropulse is then injected into a 169-m circumference accumulator ring, using charge-changing injection at a foil, to produce a 560-ns burst of 1.3x10^{14} protons at the two spallation targets via a transport line that contains switching elements to supply separate pulse trains at 40 and 20 Hz to the two targets.

A review of the design was held by a panel of external experts and an extensive feasibility study document has been prepared as well as previous publication [6]. We concentrate here on the major issues that have been raised by the study and review the evolution from LAMPF and PSR operating experience to the present design.

A. Linac front end

The injector consists of an H$^-$-ion source that must operate reliably at a duty factor of 8.6% and provide an adequate emittance (~0.02 π cm mrad rms normalized) at a nominal 40-mA peak current. While several candidate sources can produce either the required emittance, current, or duty factor, there exists no one source capable of meeting these three specifications. However, it is believed that with modest development, a suitable source can be obtained. A recent workshop [7] at Lawrence Berkeley Laboratory, under the auspices of a site-independent study, has further explored source development for this application.

The problem of chopping the beam (235 ns beam off, 436 ns beam on), to maintain a clean (<10^{-4} contamination) gap for extraction from the ring, seems more difficult [8]. The LAMPF chopper (a traveling-wave deflector) operates in a long low-energy transport line (LEBT) at 750 keV. Neutralization effects and other difficulties may preclude chopping in the proposed 100-keV LEBT; since the RFQ accelerates to 7 MeV and must be closely coupled to the first DTL, no convenient place exists for this form of chopping. Splitting up the RFQ into low- and high-energy sections with chopping between may succeed without undue emittance

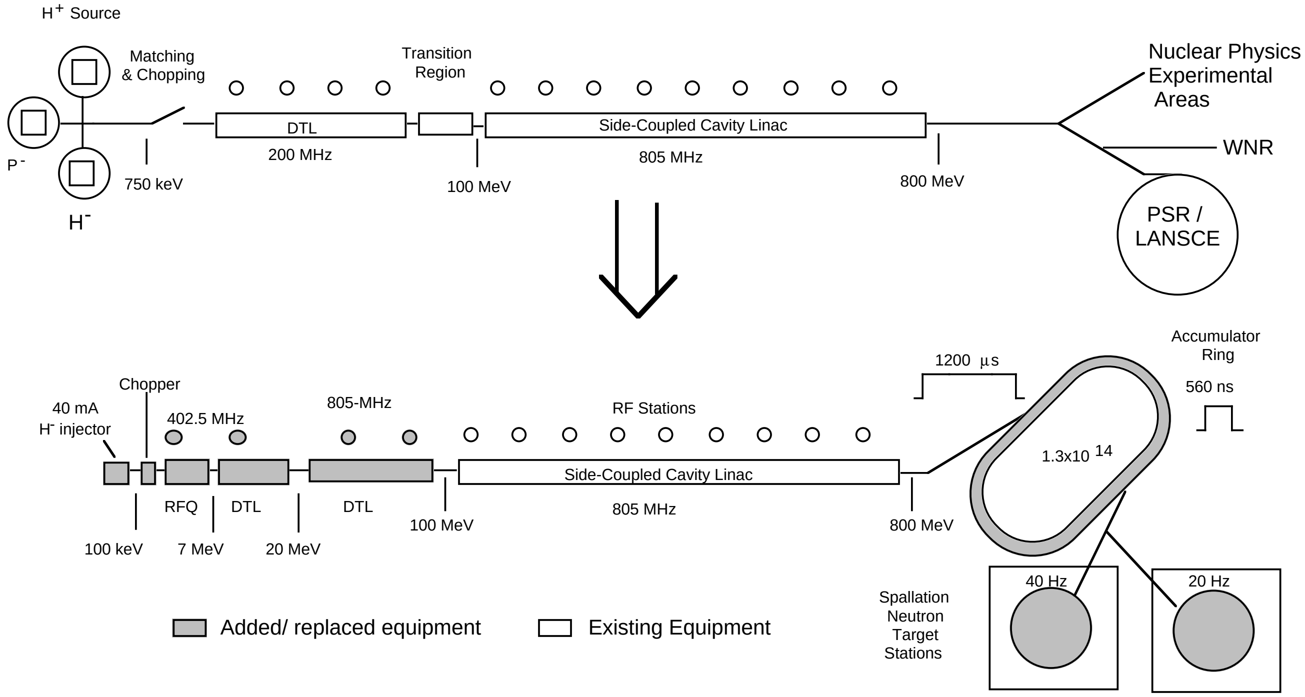

Figure 1. Schematic layout of the 1-MW upgrade. The present configuration of LAMPF is shown at the top.

growth. However, the longitudinal and transverse focusing arrangements needed become very elaborate. High-energy chopping requires undue pulsed power and high beam-power deposition to dump the unwanted portion of the beam.

Chopping in the source by some rapid-modulation method appears very attractive. Preliminary progress toward this end has been made by placing a toroidal collar near the extraction aperture of a Penning discharge source [9]. Pulsing the collar to 38 V and 100 A provides better than 90% chopping efficiency and 1-μs rise time. These results are limited by equipment and more sophisticated experiments are planned. The technique may be useful in reducing dumped beam power at a second stage of chopping at higher energy even if desired efficiencies are not obtained.

The RFQ and DTL designs are based on extrapolation of experience with linac facilities constructed for projects such as the Ground Test Accelerator (GTA) [10] and other designs. By comparison, the currents and beam quality required here are relatively modest and the front end should perform adequately at substantially higher currents.

B. The Side-Coupled Linac

The SCL is required to operate at nearly twice the peak current (29.7 mA) routinely experienced during present operation (13 to 17 mA). However, the charge per rf bucket is actually less because the beam frequency is doubled, thus easing the beam-dynamics stress. Moreover, the peak-average current (19.3 mA averaged over the 1.2-ms macropulse) is only slightly increased.

It remains to show that the rapid current variation during the 1.49-MHz chopping cycle does not affect linac operation. We expect that the rf fields in the SCL tanks will experience cyclic variations of about 1% in amplitude and 0.3° in phase over each 671-ns chopping cycle, a phenomenon we call "drop." Simulations show that a 5% amplitude drop would not appreciably affect the output energy or beam quality. Because of the increased power flow along each linac module from average beam loading, the field at the tank ends decreases relative to that at the rf-feed point in the presence of beam. This "droop" should not be a concern because of the small current increase from proven operation.

To validate these calculations and to assess general linac robustness, beam experiments on the linac were performed with chopped and unchopped beam at peak-current levels of up to 27 mA at 201.25 MHz. A droop of less than 2% was measured at each end of a 211-MeV module. The separate and combined effects of drop and droop were inferred from ΔT measurements. In accord with the beam-dynamics simulations, inappreciable effects were seen at the experimental current levels.

The results of these experiments (which included testing of new adaptive feed-forward rf-control techniques developed for GTA) and other assessments show the linac to be very robust for the 1-MW scenario. Further work is necessary to elucidate the high loss rate noted for H^- beams and more sophisticated tuning algorithms are under study. At peak currents above 100 mA, substantial modifications would be required to prevent deterioration of beam quality. These include dividing the tanks into smaller units in order to increase the number of rf feeds and decrease the focusing period.

C. Accumulator ring

The proposed accumulator ring [11] has a doublet lattice, is racetrack shaped and features dispersionless straight sections for extraction and a chicane region that places the injection point outside the ring body. The nominal tunes are 4.23 and 5.19 and the maximum beta functions are 16.62 m and 17.93 m for the x and y planes, respectively. Maximum dispersion in the achromatic arcs is 7.70 m with a momentum acceptance of ±1%. The ring acceptance is maintained at 33 π cm mrad for a nominal beam (laboratory) emittance of 15 π cm mrad.

Particular attention was paid to loss mechanisms that have been predominant in causing activation in the PSR. Loss should be diminished by the nature of the lattice, improved injection matching, and larger apertures. Other loss mechanisms require special measures.

A particular loss mechanism that was first noted on the PSR, and must play a role in any foil-stripping injection scheme, involves the production, by the foil, of neutral hydrogen atoms in excited states[12]. These neutrals then move outside the ring acceptance due to subsequent relative deflection by the field of a downstream magnet; most are stripped by the magnet's field and are lost in downstream areas. For the PSR, about 0.25% of the injected beam is thus lost. A mechanism has been devised, involving placement of the stripper foil in a magnetic field, to decrease this loss by over two orders of magnitude and is described elsewhere [13].

Scattering of the injected and stored beam by the foil leads to inevitable losses. Nuclear scattering accounts for some 15 nA which is lost immediately downstream of the foil. Coulomb scattering and other unspecified sources are assumed to lead to 150 nA of loss. A series of collimators, directly downstream of the injection section and with magnetized tips, have been devised to localize this loss so that most of the ring can be maintained without remote handling. The ring momentum acceptance is also limited by a collimator in a dispersive arc. Performance of a first-order collimator scheme has been verified by simulations.

Further loss mechanisms are linked to the beam formation process and the detailed beam dynamics.

The longitudinal injection process is important in maintaining a clear gap (~100 ns) in the beam for rise of the extraction kicker and in achieving a maximum bunching factor (~0.6). A large bunching factor is important in minimizing the space-charge tune shift, hence affecting the number of particles that can be stored. A "barrier-bucket" rf-bunching waveform, consisting of the 1.49-MHz fundamental and four harmonics, is selected for this purpose. The bucket exerts a force on accumulated particles only near the bucket extremes. By sweeping the injected-beam energy through four cycles by ±4 MeV and using measured results for the beam-energy spread, adequate confinement of particles can be achieved, but with a resultant rf-power cost of over 1.5 MW in the 13 ferrite-loaded buncher cavities. With this arrangement, the gap remains particle free to the 10^{-4} level and a bunching factor of 0.55 is achieved.

The large rf-power requirement is inevitable under the assumptions for injected-beam momentum spread but is undesirable, and presents a large longitudinal impedance to the beam because of the large number of cavities needed. The rf power may be reducible by rf-compaction of the injected beam-energy spread; however, the beam longitudinal halo may be highly nonlinear and not amenable to such measures. It is also possible to reduce the rf power by decreasing the value of the ring transition gamma (γ_T), at the possible cost of beam stability. Substantial reduction of γ_T is only possible by abdicating the feature of the dispersionless straight section that contains the injection chicane. Thence, the injection-painting scheme, uncoupled between longitudinal and transverse planes, must be forsaken as well as the last vestige of ring symmetry in the second-order-achromat-configured arcs. Our initial studies conclude that high rf-power use may be necessary to maintain an acceptable loss budget.

Maintenance of a beam-free gap and a large bunching factor may also bear on the problem of beam stability. A rapidly rising instability has been observed in the PSR that presently limits PSR peak currents [14]. The effect has the signature of a two-stream instability and is attributed to the presence of protons in the extraction gap, from insufficient rf capture, with consequent trapping of electrons. Further exploration of this instability is essential to any new facility.

Transverse-beam formation is accomplished by separate vertical and horizontal bumps using four pulsed magnets in each plane. The achromatic injection-transport line maintains the injected beam at a constant location on the foil. The foil is assumed to have a free corner and, with bump sequencing to produce a uniform distribution, less than 10 encounters with the foil will be experienced on average by each injected particle. The bumps are maximum at the start of injection and relax to zero at the end. This particular injection scheme produces an octupolar distribution in the beam that is of consequence in the beam evolution. Other sequencing arrangements under consideration can grow an elliptical beam, but do not provide an immediate tune shift to the operating point. Foil heating is substantial, with peak temperatures approaching 2500 K; experiments are called for to determine foil durability.

The beam tune shift is about 0.11, to a region of tune space that is free of low-order resonances. However, the tune spread is sufficiently large to require ring-chromaticity correction. Resonance correction through fifth order is planned to provide ample margin in tune space. The lack of supersymmetry in the ring is not seen as a problem during the short storage time.

IV. A LINAC-DRIVEN LPSS

The Long-Pulse mode requires 1 MW of delivered beam power at 60 Hz with 1-ms macropulse length, implying a peak current of 21 mA. The peak-current and duty factor requirements of the LPSS are hence similar to those of the SPSS. However, we have considered an option that addresses near-term reliable low-beam-loss operation, with substantially lower cost but with little possibility of upgrading to provide higher duty factors or peak current.

The present LAMPF linac operates very reliably with low activation at peak H^+ currents of about 14 mA. Beam powers exceeding 1 MW have been routinely produced at 120 Hz operation. Hence the linac is currently suitable for LPSS operation at about 0.6 MW. However, beam loss increases very rapidly with peak current and beam loading in the 201.25- MHz DTL exceeds the capacity of the rf systems. A study [15] shows that transient loss occurs in the DTL at the start of the macropulse due to the effective speed of the rf-control loops. Most of the non-transient loss is due to the longitudinal beam tails injected into the DTL that are a consequence of initial bunching by single-frequency cavities in the low-energy transport line before the DTL. Additional loss occurs because of the lack of longitudinal matching in the transition region between the DTL and SCL.

The LPSS study has proposed the changes shown in Figure 2. The changes include features that preserve capabilities for providing beam to the present facilities, LANSCE (with possible upgrades to 60 Hz) and the Weapons Neutron Research (WNR). Both facilities utilize H^- beam and require chopping. The suggested changes are:

1) Replace the present injectors and DTL first tank with a 201.25-MHz Radio-Frequency Quadrupole (RFQ) linac to accelerate to an energy of 5.395 MeV. The H^+ and H^- beams are focused, chopped, and merged by a new transport line at 100 keV, before the RFQ. A two-buncher matching section is placed after the RFQ. This arrangement produces the appropriate transverse and longitudinal match to the second tank of the DTL.
2) Replace the 201.25 MHz rf system with a new-tube version that will produce adequate peak and average power.
3) Install an 805-MHz bucket-rotator cavity in the transition region that will provide a good longitudinal match to the SCL.
4) Upgrade the low-level rf-control system on the SCL for operational ease and removal of initial transient loss on the macropulse.
5) Provide an upgraded set of beam-diagnostic systems.
6) Provide transport to the LPSS target
7) Install a laser system that neutralizes H^- beam to provide chopping for WNR operation.
8) Provide a computer-control-system upgrade in support of the modifications.

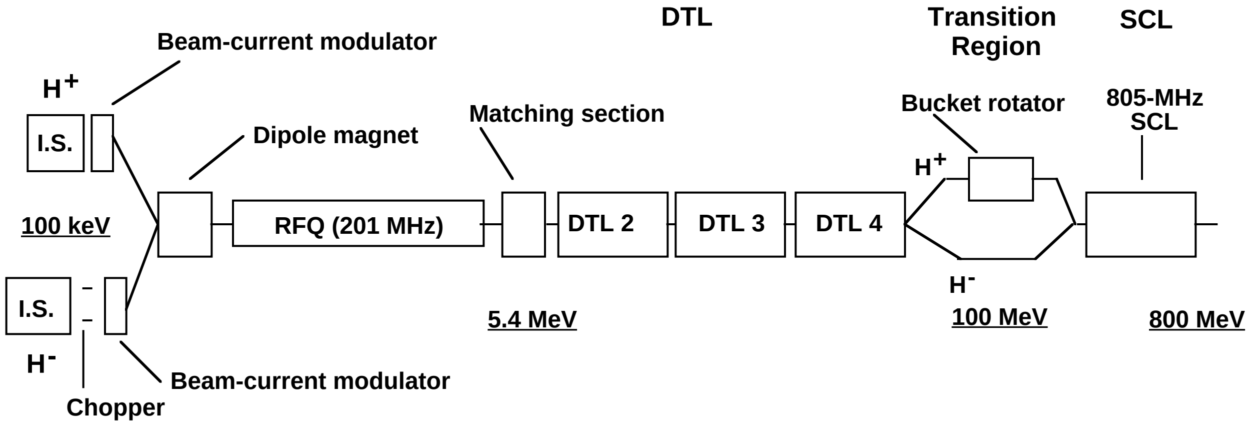

Figure 2 Schematic layout of the LAMPF linac after modification for the LPSS mode.

The inherent ability of the RFQ to produce cleanly bunched beams, along with excellent matching to the DTL eliminates the longitudinal loss while an adaptive feed-forward-control system installed on the 805-MHz SCL rf system controls the transient loss. A peak-current capability of over 28 mA is expected with these modifications, limited by the rf capacity of the SCL. Negligible beam losses are expected.

Requirements for LANSCE and WNR operation are met by two separate chopping operations of the H^- beam. The 2.8-MHz LANSCE chopper resides in the 100-keV transport line just after the source. Although, as previously noted, chopping is difficult in this region, the high line energy and low-peak current (15 mA) should allow successful operation. Developmental studies are under way. WNR requires chopping for individual micropulse selection at 5.6 MHz. Such chopping is incompatible with the RFQ and is to be done, on the basis of previous feasibility studies, at 800 MeV in a transport line by the neutralization of individual micropulses in the LANSCE macropulse.

The LPSS target is to be located in Area A, some 100 meters directly downstream of the linac. Area A currently contains several facilities and instruments used for nuclear-physics work. These will be removed and a target, surrounded by a monolith shield with remote-target-handling capabilities, installed. The proton beam strikes a 7-cm-diameter water-cooled tungsten target horizontally and neutrons are delivered to the experimental instrumentation through several horizontal beamlines that penetrate the shield.

Beam is transported to the target by much of the existing transport line with a 30-m-long final expansion region. A novel expander incorporates nonlinear elements to produce a hard-edged beam on the target with parabolic profiles from the initially gaussian-distributed beam.

VI. REFERENCES

[1] I. S. K. Gardner, "ISIS Status Report," Proc. Fourth European Particle Accelerator Conference, London (1994), p3.

[2] R. J. Macek, et al., "Status of the PSR Improvement Program," Proc. 1993 PAC, p 3739.

[3] R. J. Macek, "Machine Studies at the Los Alamos Proton Storage Ring," Proc. Twelfth Meet. International Collaboration on Advanced Neutron Sources (ICANS XII), Abingdon, England (May 1993), Vol 2, p A-25.

[4] G. Russell, LER, Los Alamos National Laboratory, private communication.

[5] F. Mezei, "Comparison of Neutron Efficiency of Reactor and Pulsed Source Instruments," Proc. Twelfth Meet. International Collaboration on Advanced Neutron Sources, Abingdon, England (May 1993), Vol . 2, p I-377.

[6] A. J. Jason, et al., "A Los Alamos Design Study for a High-Power Spallation-Neutron-Source Driver," in Proc. 1993 PAC, p. 3760.

[7] In "Proceedings of the Workshop on Ion Source Issues Relevant to a Pulsed Spallation Neutron Source," ed. Lee Schroeder, et al., LBL-36347, Berkeley, October 24-26, 1994.

[8] S. Nath, T. P. Wangler, and R. R. Stevens Jr., "Conceptual Design of Beam Choppers for RFQ Linacs," in these proceedings.

[9] H.V. Smith, Jr., P. Allison, J. D. Schneider, and J. E. Stelzer, "Experimental Study of a Simple Method to Chop Penning SPS H^- Beams," Proc. Linear Acc. Conf., August 22, 1994, KEK, Japan.

[10] K.F. Johnson, et al., "Commissioning of the First Drift Tube Linac Module in the Ground Test Accelerator," Proc. 1993 PAC, p 1669.

[11] B. Blind, A. J. Jason, and F. Neri, "Lattice Design of the LANL Spallation-Source Compressor Ring," in Proc. 1993 PAC, p 56.

[12] R. Hutson and R. Macek, "First-Turn Losses in the LAMPF Proton Storage Ring (PSR)," Proc. 1993 PAC, p 363.

[13] A. J. Jason, et al., "Minimization of First-Turn Losses by Excited Neutrals in Charge-Changing Injection of Accumulator Rings," Proc. Fourth European Particle Accelerator Conference, London (1994), p 1219.

[14] T. Wang, et al., "Recent Study of Beam Stability in the PSR," Proc. 1993 PAC, p. 3297.

[15] R. W. Garnett, et al., " Simulation Studies of the LAMPF Proton Linac," in these proceedings.