The Los Alamos Study for a Next-Generation Spallation-Neutron-Source Driver

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*Abstract*

A study has been conducted at Los Alamos to determine the feasibility of constructing a linac/accumulator-ring configuration that provides a 790-MeV 1-MW proton beam to a new target system for the LANSCE neutron-scattering research facility. The study advocates use of the LAMPF side-coupled-cavity linac with an upgraded front end as an effective means of using present facilities and to provide a path for upgrade to 5 MW of beam power. The ring accumulates $1.3x10^{14}$ particles in 1.2 ms by charge-changing injection with subsequent single-turn extraction to provide a 560-ns burst to the spallation targets at a 60-pps rate. A brief outline of the study results is given with emphasis on recent issues studied.

## 1. INTRODUCTION

Since the commissioning of the Los Alamos Proton Storage Ring (PSR) [1] there has been a continuing program of neutron research at the Manuel Lujan, Jr. Neutron Scattering Center (LANSCE). The PSR delivers 80 kW of beam power to the LANSCE spallation target with a repetition rate of 20 Hz with charge per pulse similar to that of the ISIS facility [2]. Strong interest has recently arisen in an upgraded facility with beam powers of up to 5 MW. The study presented here is limited to a 1-MW scenario as an order-of-magnitude upgrade to the LANSCE facility. Alternative and further upgrade paths to 5 MW have also been studied but are not discussed here. Details of the early part of the study have been presented [3,4].

Figure 1 shows a schematic overview of the 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 frequencies at 20 MeV permits the future addition of a funnel for possible upgrades in current.

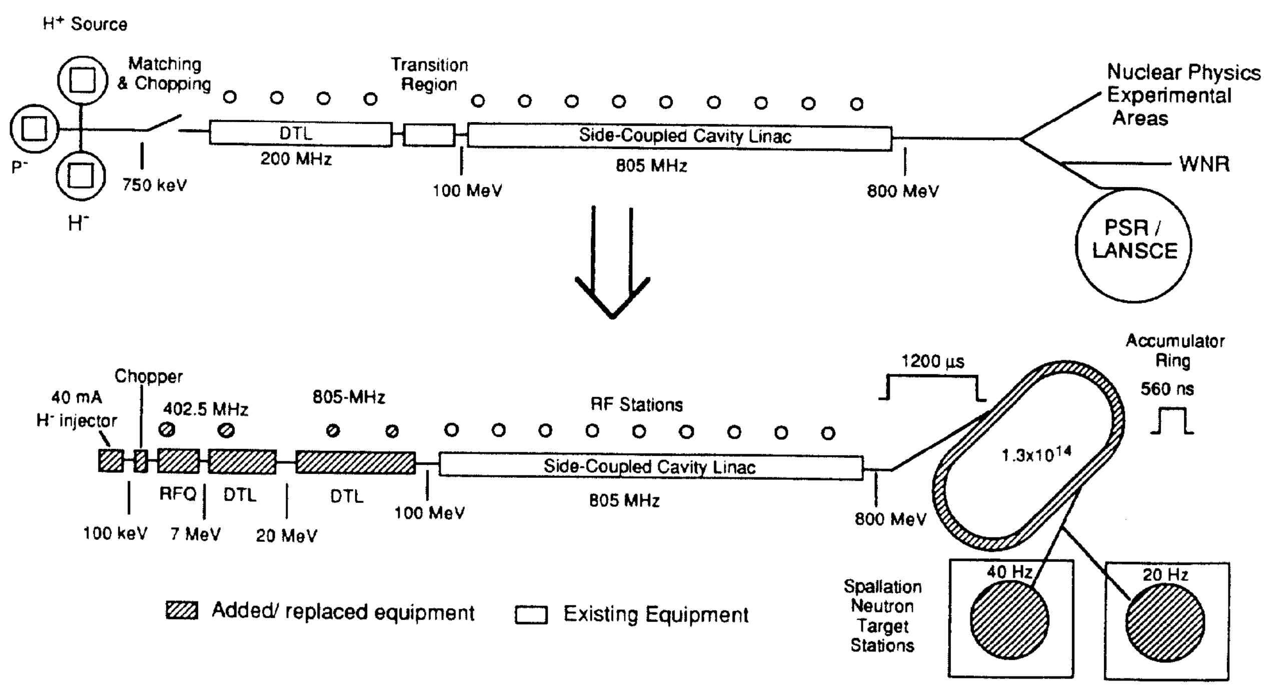


Figure 1 Schematic layout of the 1-MW upgrade. The present configuration of LAMPF is shown at the top.

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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, respectively.

A review of the design was held by a panel of external experts and an extensive feasibility study document is in press. 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.

## 2. 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 $\pi$ 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.

The problem of chopping the beam (235 ns beam off, 436 ns on), to maintain a clean ($<10^{-4}$ contamination) gap for extraction from the ring, seems more difficult. 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 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 [5]. 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) [8] 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.

## 3. SCL

The SCL is required to operate at nearly twice the peak current (29.7 mA) routinely experienced during present operation (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 (average over the 1.2-ms macropulse of 19.3 mA) is only slightly increased.

It remained 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 was inferred from $\Delta T$ 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.

## 4. ACCUMULATOR RING

The proposed accumulator ring [4] 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 $\pi$ cm mrad for a nominal beam (laboratory) emittance of 15 $\pi$ cm mrad.

### *4.1. Beam-Loss Control*

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.[7] 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 [8].

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.

### *4.2. Ring 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 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 ($\gamma_T$), at the possible cost of beam stability. Substantial reduction of $\gamma_T$ 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 [9]. 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. This particular injection scheme produces an octupolar distribution in the beam that is of consequence in the beam evolution; other sequencing arrangements are under consideration. 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.

## 6. ACKNOWLEDGEMENT

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