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PROTON STORAGE RING COMMISSIONING AT LANSCE*

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INTRODUCTION

The Proton Storage Ring (PSR),[1] now being commissioned at Los Alamos, is a fast-cycling high-current accumulator designed to provide intense 800-MeV proton pulses for driving the Los Alamos Neutron Scattering Center (LANSCE) spallation source.[2] Although originally intended to operate in both a short-bunch accumulation mode (for fast neutron spectroscopy) and a long-bunch mode (for neutron scattering), the PSR as now implemented provides only a long-bunch output optimized for the requirements of a materials science research program using thermal neutrons. In this mode, the storage ring accumulates a long (up to 1000-μs) macropulse from the LAMPF linear accelerator into a short (270-ns) first-harmonic bunch and ejects it in a single turn. The design repetition rate is 12 Hz, which will provide 100 μA on the neutron-production target, assuming the design goal of 5.2×10^{13} protons from the linac in each macropulse. If beam losses can be sufficiently well controlled, the longer range plan calls for increasing the pulse repetition rate to at least 24 Hz, and perhaps to 48 Hz, to provide more current both for neutron scattering and proposed neutrino physics programs.

The PSR, which was built for a capital cost of about $22 million, was completed on schedule in late March 1985; first beam was circulated on April 25. Most of the remainder of 1985 was devoted to commissioning and developing an understanding of how the machine operated in practice. Particular attention was given to illumination of beam-loss mechanisms. By the end of 1985, the storage ring had operated briefly in production at 30-μA average current and had accumulated up to 2.6×10^{13} protons per pulse, about half the design goal. However, beam losses during accumulation and at extraction were considerably greater than estimated during design. The limitation on maximum charge accumulated in PSR in 1985 turned out to be the peak intensity available from the H^- ion source, although beam loss, apparently from a very fast instability, was observed under some conditions above 1.5×10^{13} protons per pulse (ppp). During the accelerator shutdown from January to July 1986, the 1985 commissioning results were assessed, and several improvements were made in PSR and its associated beam transport systems. The operating plan for the 1986 run

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cycle has scheduled 40% of the available time for LANSCE beam production, 40% for continued commissioning of PSR, and the remainder split between machine maintenance and nuclear and neutrino physics programs sharing beamline-D. Major 1986 goals are to demonstrate 100-μA average current through PSR at 20 Hz and to investigate the high space-charge region up to about 4 x 10^{13} ppp. The existing H^- source has been improved during the shutdown, but it is expected that a new source design will be required to reach the goal of 5.2 x 10^{13} ppp.

So far this year the storage ring has operated routinely at 25 μA for LANSCE production, and machine physics experiments have reconfirmed both the short beam lifetime during accumulation and high extraction losses. Charge levels up to 3.3 x 10^{13} ppp have been accumulated during high-intensity machine development.

GENERAL DESCRIPTION

Beam Preparation

Figure 1 shows schematically the components in the PSR project and their physical relationship. The scale is distorted to highlight the storage ring. A summary of the design operating parameters is given in Table I; Tables II and III list the significant structural and dynamical parameters.

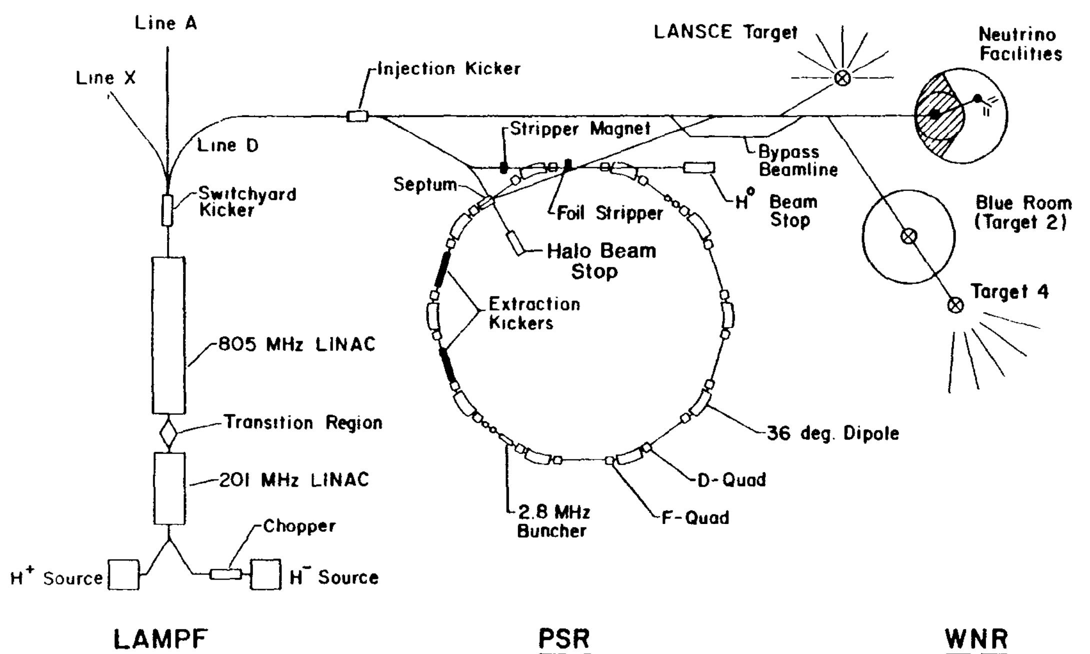

Fig. 1. Schematic drawing (not to scale) of the PSR project.

The PSR filling scheme requires multiturn injection by two-stage stripping of a high-intensity H^- beam. Design intensity of this beam is 13 mA at the output of the linac. About 6 mA was available for most of 1985, and up to 9 mA has been available so far in 1986.

TABLE I
PSR OPERATING PARAMETERS

Number of bunches in Ring	1	Injection rate	12 pps
Bunch length in Ring	270 ns	Filling time	750 μs
Buncher frequency	2.795 MHz	Extraction rate	12 pps
Protons/bunch accumulated	5.2×10^{13}	Peak circulating current	46.3 A
Accumulated turns	2100	Average current	100 μA

TABLE II
PSR STRUCTURAL PARAMETERS

Orbit circumference	90.2 m	Dipole field	1.20 T
Focusing structure	FODO	Bend radius	4.06 m
Lattice type	Separated function	Dipole aperture	10.5 cm x 28 cm
No. of periods	10	Quadrupole gradients	3.92, -2.33 T/m
Free straight section	4.51 m/cell	Quadrupole aperture	18.1 cm
Dipole length	2.55 m	Quadrupole length	0.47 m

TABLE III
PSR DYNAMICAL PARAMETERS

Circulation period	357.7 ns	δp/p (injection/extraction)	±0.001/±0.003
Proton kinetic E	797.0 MeV	Emittance, injected beam	0.05 cm•mrad
Proton ß, γ	0.842, 1.849	Emittance, extracted beam	2.0 cm•mrad
Proton rigidity	4.869 Tm	Phase advance/cell:	
Transition γ	3.02	Horizontal	115°
Tunes (Q_H, Q_V, nom)	3.2, 2.2	Vertical	79°

Considerable modification to the linac injector complex and switchyard was required to deliver H^- beam pulses to PSR while minimizing interference with other LAMPF experimental programs. The 750-keV H^- transport was completely rebuilt to accommodate multiplexing between the high-current H^- and polarized (P^-) beams and to provide the correct optics for slicing the PSR macropulse into 270-ns beam bursts every storage ring revolution period (360 ns). This is accomplished by a traveling-wave fast-rise-time electrostatic deflector (chopper).[3]

In the switchyard, totally reconfigured for PSR operations, the positive and negative beams are first separated vertically. Then the H^- macropulses for PSR are deflected horizontally into Line D by a kicker magnet and septum, whereas P^- pulses pass unperturbed into Line X. The kicker, which is driven by a high-current/low-voltage modulator, has a rise time short enough (40 μs) to permit macropulse splitting and a tightly regulated 1000-μs-long flat top.[4]

Injection

Beam is transported to PSR through the pre-existing Line D and the new injection line. All magnetic fields in this channel are below 4.0 kG to avoid field stripping the H^- ions. The injection line is skewed to permit bending in horizontal and vertical planes simultaneously.

Included in the injection line are seven pairs of remotely insertable foil strippers that are used to convert the H^- beam halo to H^+; the H^+ ions are sent to a beam dump under the ring floor. In principle, when the injection line is properly tuned, these beam scrapers should provide nearly complete rejection of all transverse phase space outside 3σ for a monochromatic beam. In practice we have found it essential to use these scrapers to reduce beam losses in the storage ring, but because momentum dispersion is nonzero in this part of the line, the trimming is not perfect.

At the end of the injection line, the H^- beam is completely converted to H^0 by a 1.8-tesla transverse magnetic field (stripper magnet). The neutral beam passes through a hole drilled in the yoke of a storage ring dipole and then contacts the (distorted) closed orbit while traversing a thin (200-$\mu g/cm^2$) carbon foil, where it is stripped to H^+ with about 90% efficiency. The unstripped H^0 beam leaves the ring through a hole in the next downstream ring dipole and is deposited in a well-shielded beam dump.

The magnetic stripping process implies an intrinsic emittance growth in the injected beam that depends on the magnet gap and horizontal beam size. A gap of one centimeter for the present stripper magnet adds a divergence of 0.36 mrad and for the chosen beam size causes a nearly threefold increase in emittance. This emittance growth severely constrains matching to the ring. A nearly homothetic match to the ring phase space can be accomplished in the vertical direction, but the horizontal match necessarily fills nearly the entire one-rms horizontal area alloted for a 2 cm-mrad beam. This situation is shown in Fig. 2.

The closed orbit is distorted (bumped) vertically during beam accumulation by a set of six pulsed magnets to allow control of phase space filling in that plane as well as minimization of beam-foil interaction. The distortion is a maximum at the beginning of accumulation and is programmed to zero by the end of the cycle. To maximize effectiveness of the orbit bump, the four quadrupoles at the end of the injection line are used to provide a good match to the storage ring in the y-y' phase plane.

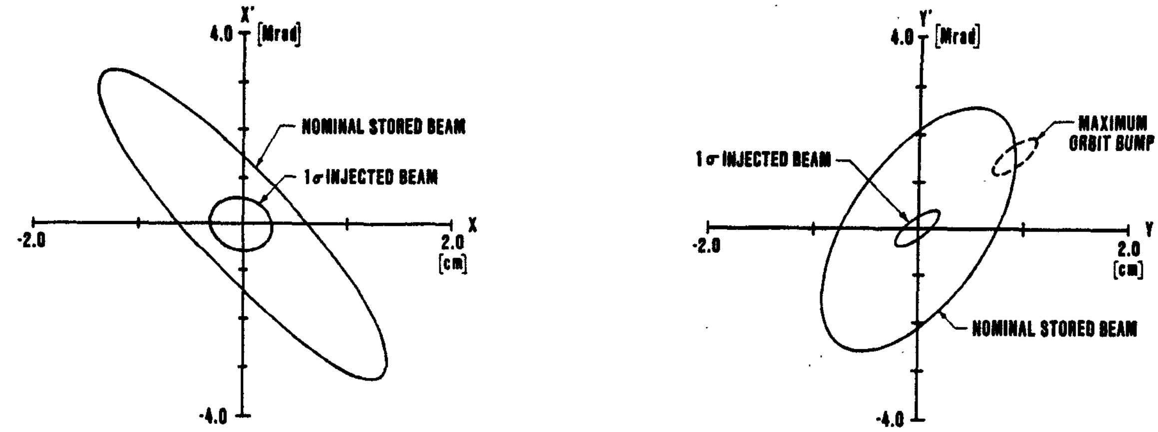

Fig. 2. Transverse phase space areas for PSR injected (small ellipses) and accumulated (large ellipses) beams. The accumulated beam emittance is taken to be 2 cm-mrad, corresponding to the Laslett tune-shift stability limit for the PSR operating parameters. The horizontal phase space area of the injected beam is shown in the left figure. The evident mismatch is necessitated by the stripper-magnet optics, which has also increased the beam emittance. In the right figure, the vertical injected beam (0.05 cm-mrad rms emittance) is shown dashed at the orbit bump trajectory extremum. The small mismatch shown is necessary to optimize transmission through the stripper magnet.

The Storage Ring

The ring design is basically a perfectly symmetric 10-cell FODO separated-function lattice. With a circumference of 90.2 m, the beam circulation period is 357.7 ns at the nominal linac energy of 797.0 MeV. For simplicity in discussion, we usually round these numbers to 360 ns and 800 MeV, respectively.

The 10 ring dipoles have parallel ends and are assembled from steel laminations. They are driven in series by a single power supply; transistor shunts are provided to allow adjustment of effective magnet lengths. Error multipoles are corrected in the integral sense by appropriately contoured solid steel pole end blocks. The F and D quadrupoles, fabricated from solid steel pieces, are identical except for their current excitation. Each set is driven by a separate power supply. The vacuum envelope is stainless steel, with each section pumped by two 600 ℓ/s ion-pumps. A pressure of less than 2 x 10^{-8} torr is maintained in the ring.

A single, first-harmonic rf buncher is provided in the storage ring to maintain a beam-free region for low-loss single-turn extraction. On each successive turn during accumulation, a new 270-ns beam bunch selected by the linac H^- injection line chopper is added synchronously and at zero relative phase to the previously inserted bunch stack in the rf bucket. The bucket amplitude is programmed to increase as accumulation proceeds for space-charge confinement. A secondary function of the buncher is to increase the momentum spread of the stored beam, providing stabilization by Landau damping against wall-induced coherent motion at high space-charge levels. The buncher itself consists of a conventional single-gap, ferrite-loaded 1/4-wave coaxial cavity operating at 2.795 MHz. Because of the very large peak circulating beam currents (up to 46 A), the rf amplifier has been designed with an exceptionally low output impedance (20 Ω) to reduce beam loading to a negligible level.[5] Second and third rf harmonics have been added to the buncher system in 1986 to help homogenize the longitudinal density distribution and control the beam momentum spread.

Extraction

Single-turn extraction is achieved by two 4-m-long balanced strip-line kickers, each energized by thyratron-switched Blumlein pulse lines. The kickers generate 300-ns-long, ±45-kV pulses with 60-ns rise times. Working in combination with the lattice magnet elements, the kickers deflect the stored beam 8.5 cm horizontally into the throat of a 5-kG septum magnet, the first element of the extraction transport channel. The channel consists of regularly spaced, large-aperture quadrupole doublets; it delivers the extracted beam to Line D from where it is transported to the LANSCE neutron-production target. Several quadrupoles were added to this portion of the original beamline to facilitate good transmission of high peak-current beams. A vertically oriented dipole located a short distance along the extraction channel allows the beam to be switched to a separate beam dump so that the storage ring can be tuned at low average current before the extracted beam is directed to the target.

COMMISSIONING

Chronology

PSR construction was completed on schedule in late March 1985, and first beam was circulated on April 25. Beam was first extracted from PSR on May 24. The early summer was devoted to studying ring performance at low average currents and up to 2×10^{12} protons per pulse. Much of this period was devoted to debugging equipment and controls software and to improving operational reliability. The closed orbit was corrected to within 1 mm, using active shunts on the dipoles for horizontal plane correction. Displacement of quadrupoles was necessary for vertical plane correction.

From the beginning of the PSR design, it had been understood that keeping beam losses well below 1% would be a central requirement for operation at 100 μA. Within a few weeks after turn-on, it became apparent that fractional beam losses in PSR were considerably higher than anticipated. Average currents of 1-2 μA induced activation levels exceeding 3 rem/hr (contact) in some components, even after brief periods of operation. Machine experiments therefore quickly focused on trying to obtain a clear picture of beam losses and on studying the match from the injection line into the ring as one of the keys to understanding the loss mechanisms.

During the fall of 1985, a series of machine experiments exposed the main features of the beam loss. First beam (2 μA) on the LANSCE production target occurred on September 14. In November, with some improvements in instrumentation and tuning and also a decision to accept significant activation levels, trial three-day production runs were made at 10-μA and then 30-μA average currents. In mid-December, machine experiments were conducted at high peak intensities with a maximum of 2.6 x 10^{13} ppp being reached, about half the design goal. The peak accumulated charge in PSR was limited by the H^- intensity (about 7.5 mA) available at that time and the maximum macropulse length (1000 μs) allowed by the linac rf system. While tuning the ring at charge levels above 1.5 x 10^{13} ppp, some evidence of fast beam loss, possibly from coherent transverse motion, was observed.

Activation levels resulting from the 30-μA production run and the high-intensity machine experiments were high, especially at the extraction septum, where >30 rem/hr (contact) was measured shortly after beam shutdown. A few other locations had levels as high as 1-2 rem/hr (e.g., the foil stripper and the quadrupoles in the two following straight sections), but most of the storage ring had activation levels below 100-mrem/hr.

The PSR was shut down during the first six months of 1986, along with the linac, for the usual budgetary reasons. During the shutdown, improvements were made to several hardware systems, especially in the area of beam diagnostics. Procurement of sextupoles for chromaticity control was initiated, higher harmonics were added to the 2.8-MHz buncher, the VAX 11/750 control computer was supplemented by a microVAX and a software development console, and the neutral-beam transmission holes in the injection-section ring dipoles were enlarged to reduce losses from the injected beam halo.

Equipment Operation

Much of the initial work in the 1985 commissioning program was devoted to operational check-out of the many complex pulsed systems and to bringing the diagnostics into operation. The traveling-wave chopper, which provided variable-length bunches up to 300 ns long for injection into the ring, performed nearly flawlessly from the start. The flexibility of the pattern generator that drives the amplifiers has been invaluable for choosing the wide variety of pulse lengths and sequences needed for ring tuning studies.[6] Typically, ±500-V pulses having <5-ns rise times are needed to provide adequate chopping of the beam.

The switchyard kickers have also been relatively trouble-free and have easily provided the ultra-flat deflection pulses required. The two modulators have been tested up to 40 Hz at a pulse current of about 2000 A. We believe that pulse rates up to 60 Hz are possible with only minor modifications, which will allow multiplexing LANSCE with other Line D programs requiring different macropulse chopping sequences.

The extraction septum magnets[7] have operated reliably in spite of the activation of this region. The initial switchyard septum magnet experienced coil overheating problems that interfered seriously with commissioning during the early months. It was replaced by a septum with an improved coil design (parallel water circuits instead of one series connected loop) that has operated trouble-free.

The 2400-A transistorized pulse drivers[8] for the (six-unit) vertical orbit bump system have proved vulnerable to failures caused by imperfect protection against excess duty factor. Protection has been improved in 1986. The driver pulse shape has been easy to adjust through an interactive program using the console graphics/touch screens.

The 2.8-MHz rf buncher amplifier has functioned generally satisfactorily, except for minor control problems. Second and third rf harmonics are being added in 1986 to provide a linear bunching waveform over a wider phase range. This modification should reduce the peak longitudinal charge density in the accumulated bunch, decreasing the maximum space-charge tune shift at high currents. Because the cavity bandwidth is broad and the overall duty-factor is low, the harmonics can be applied directly at the same cavity gap as the fundamental.

The extraction kicker modulators have operated well and stably, considering their complex and unusual design.[9] They have provided suitably flat, 300-ns-long ±45-kV pulses to drive the two 4-m-long strip-line deflectors. The firing circuit for the modulators allows the operator to adjust the desired extraction time in 1-μs steps. A 1-ns resolution circuit then produces a beam-associated rotation delay that synchronizes the actual kick with the azimuthal position of the beam in the ring. Rotation delays were set correctly for each modulator by observing the stored bunch during its last revolution before extraction (using a beam transformer) and comparing it with the extracted bunch as seen by a similar transformer in the extraction line.

A gradual and significant increase in kicker-pulse rise time from the 50-ns design value has been observed, and is attributed to aging of the high-voltage switch thyratron. Troublesome circuit components have included the (copper-sulfate-cooled) line-terminating loads and the circuits used to charge the pulse forming networks.

Beam Diagnostics

The strip-line beam position monitor system, which is tuned to process the 200-MHz microstructure imposed by the linac, has been described in several publications.[10] It forms the backbone of the beam diagnostics both for the storage ring and the beam transport lines. It has performed efficiently and has provided us with vital data acquired during commissioning. In addition to its standard use for beam centering, it is also possible to observe fast and slow energy variation of the H^- beam with this system. In the storage ring, it is used specifically to measure the closed orbit, fractional betatron tunes, relative beam intensity, and fast coherent transverse beam motion.

The system competently handles the wide pulse-intensity range present during beam accumulation in the ring (10^3), but filtering is necessary for observing the extracted beam after the 200-MHz frequency component has washed out. The main drawback has been that all 60 detectors are multiplexed through a single position-processing system for each plane, which sometimes causes an operational bottleneck. The reed-relay multiplexers used in the ring (to assure wide dynamic range) have had lifetime problems because of the continuous use of the system to monitor the closed orbit. Terminating resistor contacts at the strip-line detectors have also proved failure prone. Beam profile diagnostics in the transport lines consist of a mixture of wire-scanners, harps,[11] and Al_2O_3 viewing screens. In three-unit groups, the harps and wire-scanners are used to make on-line beam-emittance measurements. Although the harps have proved useful for determining the core width (1σ) of the beam profile, their noise background has been too large to yield good information about the profile tails. The wire scanners do somewhat better in this regard, but are not installed in all beamlines and are slow. They too cannot reveal details of intensity distributions below the 1% level. This kind of information is crucial for understanding and minimizing injection losses, but is not accurately determined by present PSR diagnostics.

A nonintercepting profile monitor is being developed to follow the transverse shape evolution of beam in the storage ring. This system, which relies on collection of electrons from the background gas atoms ionized by the circulating beam, may be available for use later this year. In the meantime, the time-dependence of the stored beam profile can be measured by ejection (at different accumulation times) onto an extraction channel wire-scanner or harp.

Other diagnostics[12] that have been important in commissioning are beam transformers for measuring the instantaneous stored current and longitudinal bunch profile, a wall-current monitor, and (in 1986) a split cylinder capacitive position pickup that can observe beam motion in the frequency range below 10 MHz. A time-of-flight beam-momentum detector installed in Line D is used to measure fast fluctuations and slow variations in the injected-beam energy and will eventually be part of a feedback loop to stabilize the accelerator energy.

Last, but far from least, are the beam loss monitors. In basic form these devices are liquid scintillators coupled to photomultipliers for observing beam loss at various points in the storage ring and beam transport lines. Some of the loss signals are integrated and fed to an automatic loss-limiting (fast-protect) system that shuts off beam when preset limits are exceeded. Other units are used for direct turn-by-turn observation of beam losses associated (at specific locations) with injection, accumulation, and extraction. The problems encountered with use of these loss monitors lie in quantitatively relating the loss-signal strength to actual beam loss, and (at high-peak-loss locations) obtaining sufficient dynamic range.

RESULTS

Experiments

From nearly the beginning of PSR commissioning, the concentration of experiments has been on understanding and minimizing sources of beam loss at intensities below the current level where space-charge effects would be important. We believe these losses are from single-particle effects, namely the interaction of individual beam particles with the physical environment, exclusive of the beam itself. Furthermore, the picture we have constructed distinguishes between single particle losses of several types, occurring at different times and locations. Although fast, coherent beam loss has been observed briefly at very high accumulated charge levels (> 1.5 x 10^{13} ppp), not much investigation time has been devoted to such space-charge related phenomena.

Other machine measurements have been carried out, including the horizontal and vertical chromaticity, a map of the significant resonance lines in the betatron tune space near the normal operating point, determination of single-particle phase-space trajectories as a function of betatron amplitude, and observation of the longitudinal bunch shape as accumulation proceeds.

Injection Losses

Injection losses are due to long beam tails in x-x' and y-y' phase space, and also to tails of the $\delta p/p$ (relative momentum) distribution in finite-dispersion regions. The acceptance of Line D and the PSR injection line is large enough to transport the H^- beam with very small losses up to the stripper magnet. The beam is focused within the 1-cm vertical aperture of the stripper magnet to about a 1-mm (1σ) vertical waist. Steering or lens misadjustment errors at this location can cause significant beam to be scraped off vertically by the poles of this magnet, but proper insertion of the upstream halo strippers generally avoids this problem. A new halo stripper was installed in 1986 with orientation and longitudinal position chosen to image the stripper magnet gap, providing specific protection for this device.

During 1985, considerable injection loss was caused by beam halo scraping at the back-leg holes in the two ring dipoles traversed by incoming H^o beam and outgoing unstripped H^o beam. This situation has been remedied in 1986 by enlargement of these holes.

Observation of turn-by-turn losses during injection has made it clear that there are important losses in the storage ring during the first few revolutions caused by transverse phase-space tails and dispersed momentum tails scraping on limiting apertures. Absence of a homothetic match in the x-x' plane between incoming beam and the storage ring exacerbates the problem, and a momentum mismatch in the angular component of phase space at injection contributes by increasing the transverse displacement of momentum tails. Comparison of the time-dependence of loss signals at several ring locations indicates that such early-turn losses are greatest just downstream from the injection straight section and reduce to zero in about 10 turns. However, their absolute magnitude is hard to estimate.

These losses can be reduced by a factor 10 by inserting the injection-line halo scrapers (thus removing about 5% of the beam) and also by tuning the linac to minimize momentum tails. While the 1σ width of the H^- momentum distribution is normally about 0.05%, a poor accelerator tune can result in momentum tails exceeding 0.5%. Because the halo scraper configuration does not provide "clean" scraping in momentum space, at this time it is not possible to eliminate momentum tails in the injection line without excessive reduction of beam intensity.

An additional contribution to injection loss comes from angular dispersion introduced by the stripper magnet. This dispersion was measured directly by comparing the H^0 beam profile with that of an unstripped H^- beam. As shown in Fig. 3, this dispersion, while basically in accord with prediction, has a larger-than-Gaussian tail that adds significantly to the magnitude of the x-x' phase space. Even a zero emittance beam passing through the stripper magnet would emerge with a finite angular distribution from this process. Early-turn losses in the ring were completely eliminated only in a special experimental configuration

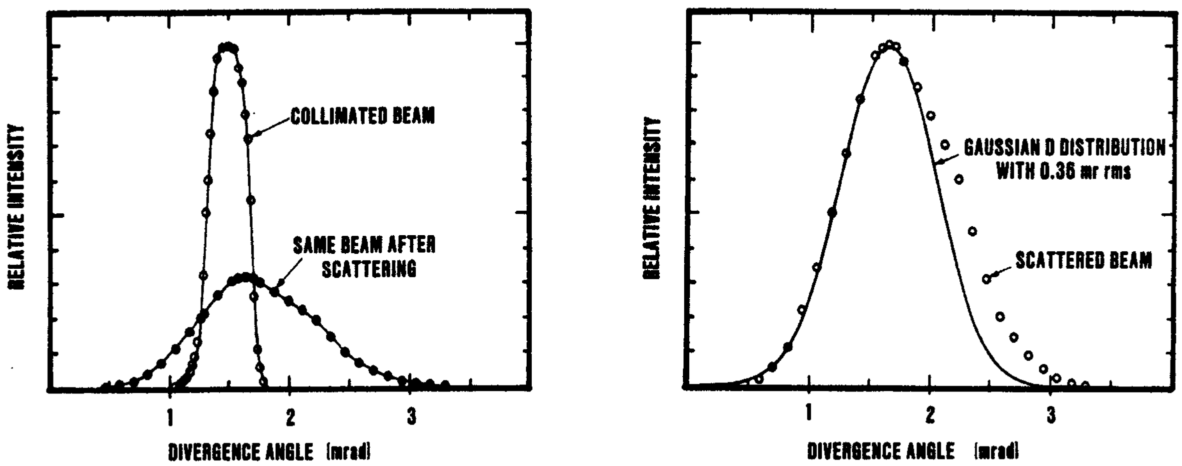

Fig. 3. Left Figure - Angular scattering of an initially collimated beam by the stripper magnet. Data were taken by allowing the beam to drift after magnetic stripping and measuring the horizontal distribution.

Right Figure - Comparison of stripper magnet scattering data with a Gaussian distribution of 0.36 mrad rms width, the expected rms divergence addition for the stripper magnet. The trailing edge of the distribution reflects the finite vertical beam width; off axis particles are stripped with less angular growth but are deflected further, hence producing a high divergence tail.

that employed a finely collimated H^- beam injected through a thin (60-$\mu g/cm^2$) stripper foil; the foil provided 50% conversion of H^- to H^O and was temporarily substituted for the stripper magnet to permit a study of losses in the absence of the magnetic stripping. Because of its poor conversion efficiency, such an injection foil is not a practical operational option.

Accumulation Losses

By midsummer 1985, it became clear that significant beam loss occurred during accumulation as long as the circulating protons continued to intersect the stripper foil. Several sets of experiments outlined the general characteristics of this accumulation loss, which appears to arise from scattering at the foil and is much stronger than predicted in design calculations.

In one experiment, a small amount of beam was injected into the ring and its lifetime was determined (using a current transformer), as a function of stripper foil thickness. The foils were inserted so that all protons intersected the foil on every turn, and lifetime was characterized by the time at which the stored beam intensity dropped to 1/e of its level at the end of injection. Results of this set of measurements are summarized in Fig. 4, which shows very clearly that beam lifetime is inversely proportional to stripper thickness. Concurrent beam loss measurements are also consistent with a scattering mechanism for beam loss.

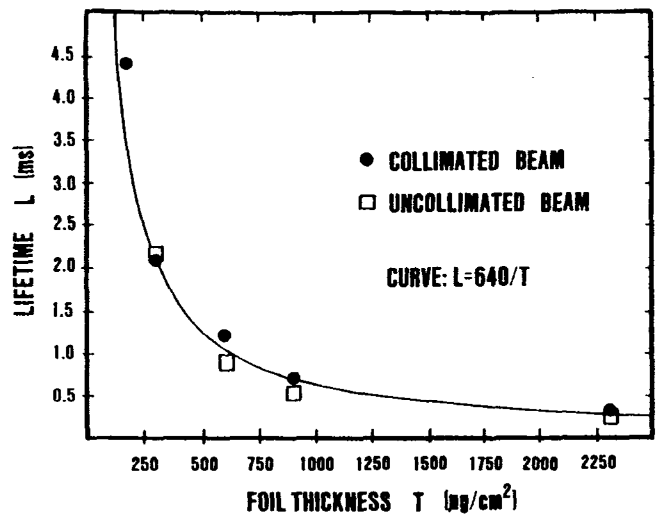

Fig. 4 Results of an experiment to determine the effect of stripper foil thickness on beam lifetime. As a result of this and other experiments, the foil thickness used for normal PSR operation has been reduced from 300 $\mu g/cm^2$ to 200 $\mu g/cm^2$.

A typical lifetime curve for a 300-$\mu g/cm^2$ stripper foil is shown in Fig. 5. This curve can be fitted fairly well by a function of the form exp $[-(t/\tau)^{1.7}]$, where τ is the beam lifetime, suggesting that beam loss proceeds through growth in the transverse beam emittance resulting from multiple interactions with the stripper foil, rather than by direct removal of protons in single collisions. The latter kind of process (such as nuclear scattering) would produce a lifetime curve with a simple exponential decay, exp $[-(t/\tau)]$, which looks very different from the observations.

Although beam loss from multiple scattering in the stripper foil was anticipated, the loss rate is much greater than was estimated during design. Recent particle tracking computations using a very accurate Monte Carlo representation of the Coulomb scattering in the foil have fallen short of simulating the observed beam-loss rate by more than an order of magnitude. Figure 6 shows the results of tracking a large number of particles around a linear version of the ring lattice, with an angular scattering function applied each turn to simulate the foil interaction. Fractional beam survival is plotted as a function of the number of revolutions for several effective limiting-aperture dimensions. The calculation assumed that particles were always lost at the extraction septum, known to be

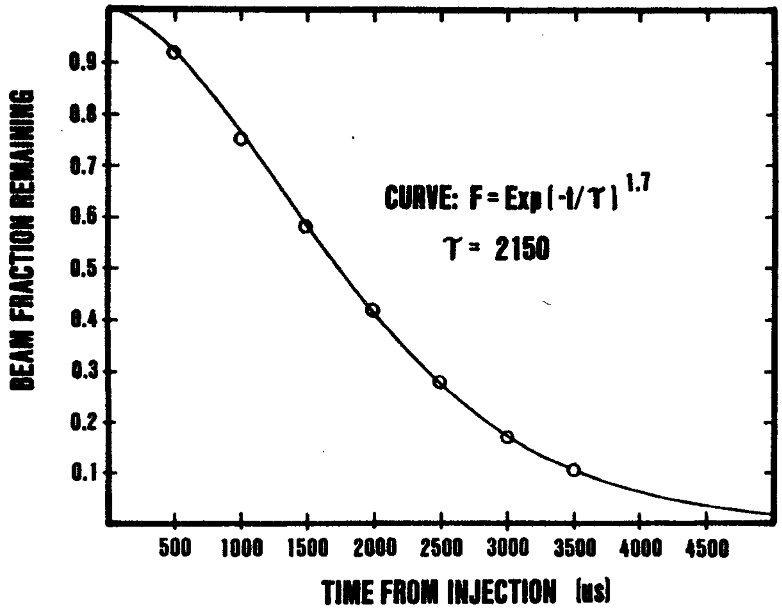

Fig 5. Lifetime curve for a 300 μg/cm² stripper foil. For this experiment, particles were allowed to circulate through the foil for several milliseconds after injection. Normal operation of the PSR extracts beam immediately after injection, but the injection period can last up to 1000 μs.

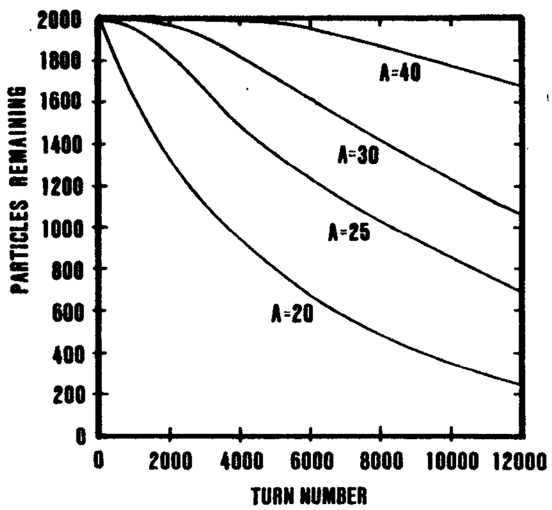

Fig. 6. Loss curves with a 300 μg/cm² foil for various assumed limiting half-apertures A. The simulation assumed 2000 initial particles with an initial Gaussian distribution of 16 mm horizontally and 8 mm vertically. It is assumed that all particles scattered by the stripper foil are lost when reaching a transverse amplitude of A (mm) at the septum. The curve for A = 25 mm is in best agreement with the measurements for the PSR.

the limiting aperture in the horizontal plane. The experimentally observed short lifetime can only be reproduced by supposing an effective aperture for the storage ring that is much smaller than the 4-cm physical half-aperture. A more sophisticated simulation using a nonlinear lattice description has been carried out with the Lie-Algebra code MARYLIE.[13] Even when a large sextupole is artificially inserted (at an F-quadrupole), the calculated beam lifetime is still much greater than has been observed.

The anomalously-short beam lifetime, presumably from scattering in the stripper foil, remains at present a mystery. Additional experiments are in progress to shed more light on this puzzle.

Extraction Losses

Beam losses in the extraction channel have been difficult to quantify because of saturation of the detectors during the short extraction pulse. The septum magnet is the most highly activated component in the ring, however, and it must be assumed that some of this activation is caused by less than optimum extraction efficiency. Additional diagnostic devices are being added in this region to study the extracted beam trajectory. Work is also under way to develop nonsaturating, quantitative beam loss monitors.

CONCLUSION

The first year of PSR commissioning has demonstrated that the basic machine design is sound and the equipment subsystems function according to specifications. Strong emphasis has been placed on increasing component and system reliability. Our primary goal, however, has been to study and reduce beam loss mechanisms so that activation remains sufficiently low to avoid remote handling during maintenance and upgrade operations. We have succeeded in this to a large extent by achieving one-third of the design average current and over half the design peak intensity with losses less than 5% and encountering no uncontrollable instabilities. The dominant loss mechanism is the accumulation loss that is likely caused by a virtual or real aperture restriction.

A series of runs for our user group has demonstrated PSR's utility as a spallation neutron source with the world's highest peak intensity. During these runs, component activition remained low enough so that "hands on" maintenance was possible after a short shut-down period. In forthcoming development our main priorities will be to increase the linac-source intensity as well as to understand and eliminate the anomalous beam loss observed. We feel confident that further machine experiments and improvements, especially in the area of diagnostics, will lead to attainment of the 100 μA goal while remaining within activation constraints.

REFERENCES

1. G. Lawrence, R. Hardekopf, A. Jason, P. Clout, and G. Sawyer, "Los Alamos High-Current Proton Storage Ring; A Status Report," Proc. 1985

Particle Accelerator Conf., IEEE Trans. Nucl. Sci. 32 (5), 2662 (1985).

2. D. Bowman, "Status Report on the WNR/PSR Pulsed Spallation Neutron Source at the Los Alamos National Laboratory, Proc. of International Collaboration on Advanced Neutron Sources (ICANS-VII), Report AECL-8488, 9 (1983).

3. J. S. Lunsford and R. A. Hardekopf, "Pulsed Beam Chopper for the PSR at LAMPF," Proc. 1983 Particle Accelerator Conf., IEEE Trans. on Nucl. Sci., 30, (4), 2830 (1983).

4. R. A. Hardekopf, E. Higgins, and J. Lunsford, "Ferrite Kicker Magnet for the LAMPF Switchyard Upgrade," Proc. 1985 Particle Accelerator Conf., IEEE Trans. Nucl.Sci. 32 (5), 3634 (1985).

5. T. W. Hardek, "A Low-Impedance, 2.8-MHz, Pulsed Bunching System for the Los Alamos Proton Storage Ring," Proc. of Sixteenth Power Modulator Symposium, IEEE Conf. Record 84-CH2056-0, 207 (1984)

6. R. A. Hardekopf, "PSR Beam-Pulsed Formation and Control," Proc. of International Collaboration on Advanced Neutron Sources (ICANS-VII) Report ACEL-8488, 134 (1983).

7. Alex Harvey and Andrew Jason, "DC Septum Magnets for the Los Alamos Proton Storage Ring," 9th Int. Conf. on Magnet Technology, Zurich, Switzerland, September 9-13, 1985, Swiss Institute for Nuclear Research (SIN) report ISBN 3-907998-00-6, 111 (1985).

8. A. J. Jason, E. F. Higgins, and A. R. Koelle, "The Los Alamos Proton Storage Ring (PSR) Injection Deflector System," Proc. 1983 Particle Accelerator Conf., IEEE Trans. on Nucl. Sci. 30, (4) 2941 (1983).

9. John F. Power, Barbara Blind, and Andrew J. Jason, "The Los Alamos Proton Storage Ring Fast-Extraction Kicker System," Proc. 1985 Particle Accelerator Conf., IEEE Trans. Nucl. Sci. 32 (5), 3021 (1985).

10. E. F. Higgins, and F. D. Wells, "A Beam Position Monitor System for the Proton Storage Ring at LAMPF," Proc. 1981 Particle Accelerator Conf., IEEE Trans. on Nucl. Sci. 28 (3), 2308 (1981).

11. D. M. Lee, D. Brown, R. A. Hardekopf, J. R. Bilskie, and O. B. van Dyck "Wide Dynamic Range Beam Profile Monitor" Proc. 1985 Particle Accelerator Conf., IEEE Trans. on Nucl. Sci. 32, (5) 1967, (1985).

12. P. N. Clout, "Proton Storage Ring (PSR) Diagnostics and Control System," Proc. of International Collaboration on Advanced Neutron Sources (ICANS-VII), Report AECL-8488, 128 (1983).

13. A. J. Dragt, Center for Theoretical Physics, Dept. of Physics and Astronomy, University of Maryland, College Park, MD, 20742, "Marylie 3.0, A Program for Charged Particle Beam Transport Based on Lie Algebraic Methods," User Manual (unpublished).