PERFORMANCE OF THE LOS ALAMOS PROTON STORAGE RING*

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Abstract

The Proton Storage Ring (PSR) now in operation at Los Alamos is a high-current accumulator that generates intense 800-MeV proton pulses for driving the Los Alamos Neutron Scattering Center (LANSCE) spallation source. The ring compresses up to 1000-μs-long macropulses from the LAMPF linac into 250-ns bunches and ejects them to a neutron-production target, providing an output optimized for thermal-neutron-scattering research. The design pulse rate and peak pulse intensity of PSR are 12 Hz and $5.2 \cdot 10^{13}$ protons per pulse (ppp), yielding 100 μA average current when full performance is reached. This paper summarizes commissioning results and operational experience in the two years since first beam.

The PSR has operated in production at average currents up to 30 μA and has reached a peak intensity of $3.4 \cdot 10^{13}$ ppp. These achievements represent 30% and 65% of the design objectives. Higher current production has been inhibited by beam losses during accumulation and extraction. Therefore, experiments to understand loss mechanisms have occupied a large fraction of the commissioning effort. Correction of an extraction-channel aperture restriction identified late in 1986 should dramatically reduce extraction losses, which will permit higher current production in 1987.

Beam tests in the 10^{13}-ppp range have indicated the presence of a collective instability tentatively identified as transverse. However, by suitable parameter adjustments, the instability threshold can be pushed above the top charge-level attainable with the existing H^- source.

Description and Performance

Figure 1 shows the storage ring and its associated beamlines. A summary of important design parameters

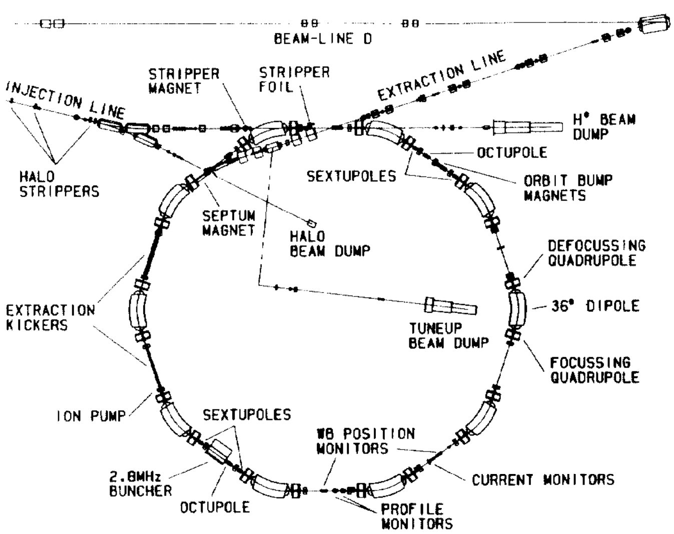

Fig. 1. Plan view of PSR.

and operational goals is given in Table I, with commissioning measurements and achievements indicated in parentheses. More information on PSR design and early operation is available in other publications.[1,2]

Beam Preparation

Macropulses up to 1000 μs long are generated by an H^- ion source serving only PSR. These are sliced into beam-bursts at the ring revolution frequency (2.795 MHz) by a

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TABLE I
STORAGE RING PARAMETERS

STORED BEAM

Bunch length	270 ns (250 ns)	Filling time	750 μs (975 μs)
Protons/bunch	$5.2 \cdot 10^{13}$ ($3.4 \cdot 10^{13}$)	Peak current	46.3 A (30.0 A)
Pulse rate	12-24 Hz (12 Hz)	Average current	100 μA (30 μA)

INJECTION/EXTRACTION		LATTICE	
Beam ion, energy	H^-, 797 MeV	Orbit circumference	90.2 m
Beta, gamma	0.842, 1.849	Focusing structure	FODO, 10-cell
H^- intensity	14 mA (10 mA)	Acceptance (x,y)	124, 167 mm-mrad
Emittance (mm-mrad)		Aperture (β_{max})	9.72 cm
H^- beam (1σ)	0.5 (0.4)	Transition gamma	3.08 (3.22)
Extracted (horiz)	7 mm-mrad	Betatron tune (x,y)	3.23, 2.21
Extracted (vert)	20 mm-mrad	Phase advance/cell	113°(x), 79°(y)
δp/p (full width)		Betatron amplitude	
Injected	± 0.001	horiz (min,max)	2.0 m, 14.1 m
Extracted	± 0.003	vert (min,max)	2.0 m, 14.2 m
Charge stripping		Dispersion (min,max)	1.1 m, 2.2 m
H^--H^0 efficiency	100%	X-chromaticity	-0.82 (-1.25)
Angular div.	0.37 (0.36) mrad	Y-chromaticity	-1.30 (-0.96)
H^0-H^+ efficiency[a]	96.3% (90.0%)	Buncher harmonic	1
Extraction septum		Buncher frequency	2.795 MHz
Beam displ.	8.3 cm	RF amplitude (max)	15 kV
Septum thickness	1.0 cm	Synchrotron tune	0.0006
Beam 1σ (horiz)	1.8 cm		

[a] For 200-μg/cm² stripper foil.

chopper in the 750-keV transport preceding the linac. The pulse length usually selected is 250 ns; for machine development, the pattern generator driving the chopper amplifiers provides a wide variety of lengths and sequences. Both the chopper and pattern-generator have performed with few flaws. The H^- source provided 7 mA (unchopped equivalent) peak intensity in 1985, which was improved to 10 mA in 1986. A new ion source will probably be needed for production of the 14-16 mA measured to reach full intensity in PSR.

In the linac switchyard, H^- macropulses are deflected into beamline-D by two kicker magnets and a septum. The kicker modulators provide pulses with tightly regulated 1-ms-long flattops. Performance of these units has been solid. They have been tested at pulse rates up to 40 Hz, and a 60-Hz upgrade is being implemented to allow multiplexing between PSR/LANSCE and other line-D programs.

Injection

Beam is transported to PSR through line-D and the injection line. Installed in the latter are seven foil-stripper stations used to convert emittance and momentum tails to protons, which are then transported to a halo beam dump. When the line is properly tuned, these scrapers reject all transverse phase space outside 3σ for a monochromatic beam, but because dispersion is nonzero, the trimming is not perfect. Usually, about 5% of the H^- beam is removed, significantly reducing injection beam losses in the PSR.

Near the ring, the H^- beam is stripped to H^0 by a 1.8-T magnet. The H^0 beam enters the lattice through a dipole and is stripped to H^+ with 90% efficiency while traversing a 200-μg/cm² carbon foil. The unstripped H^0 exits the ring through the next lattice dipole and is deposited in a shielded beam dump. Instrumentation in the H^0 dump line aids adjustment of injection steering and matching.

Although H^0 injection provides engineering advantages, it reduces optical matching flexibility. The angular divergence accompanying magnetic stripping increases

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the x-x' emittance of the injected beam by x 3, constraining the match to the ring. Even though a nearly homothetic match to the y-y' acceptance can be effected, the horizontal mismatch causes the injected beam to quickly occupy most of the x-x' area (20 mm-mrad) alotted for fully accumulated beam.[2]

The closed orbit is distorted (bumped) vertically during accumulation by six pulsed magnets to provide phase-space-filling control as well as to minimize the number of beam-foil interactions. The 2400-A transistorized bump drivers have been vulnerable to failures caused by imperfect duty-factor protection. As a result, it has not yet been possible to optimize PSR performance with the orbit-bump system. Modulator improvements in 1987 should resolve these problems.

A major PSR design concern was the survival time of the carbon strippers; few-hour lifetimes were predicted. Operational experience suggests the (radiation damage) lifetimes may be much greater than early estimates. No foils have been destroyed by beam interaction, even with peak currents up to 30 A. One 200-µg/cm^2 foil was used exclusively for 2 months without observable deterioration. The number of proton collisions with this foil is estimated at 10^{23}, equivalent to 5 days' operation at 100 µA. Beam transmission measurements, using foils (later) weighed to verify their thickness, gave the following results for H^0-H^+ conversion efficiency: 200 µg, (90%); 300 µg, (98%).

Storage-Ring Operation

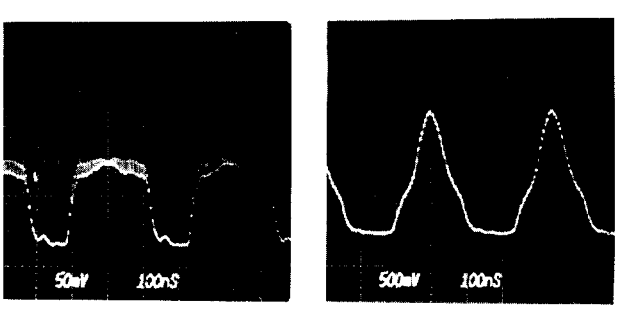
A single first-harmonic rf buncher maintains a beam-free azimuthal zone for low-loss, single-turn extraction. During injection, each turn adds a new beam bunch to the accumulated stack. These bunches are added synchronously and at zero phase in the rf bucket, whose amplitude is programmed to increase with stack intensity. During accumulation, the full-width $\delta p/p$ of the stored beam increases to an estimated value of ± 0.003.

The buncher is a single-gap, ferrite-loaded, coaxial quarter-wave cavity that provides a maximum rf amplitude of 15 kV. Even at highest circulating currents (46.3 A), beam-loading is unimportant because the amplifier has a 20-Ω output impedance. Except for minor control problems, the buncher has functioned well.

Evolution of the longitudinal bunch shape from $2{\cdot}10^{12}$ to $2{\cdot}10^{13}$ ppp is shown in Fig. 2. If the buncher phase or beam energy are incorrectly adjusted, the distribution becomes asymmetric and beam losses increase. Figure 3 shows the accumulation ramp for 975-µs injection along with the rf-amplitude program. Extraction occurs 50 µs after the end of injection.

Extraction

Single-turn extraction is achieved by two 4-m-long strip-line kickers, each energized by thyratron-switched pulse-line modulators. The kickers generate 300-ns, ±45-kV pulses with 60-ns rise times, and deflect the stored beam 8.3 cm horizontally into the throat of a 5-kG septum magnet, the first element of the extraction beamline.



2.2x10^{12} ppp   2.0x10^{13} ppp

Fig. 2. Longitudinal bunch-shape evolution.

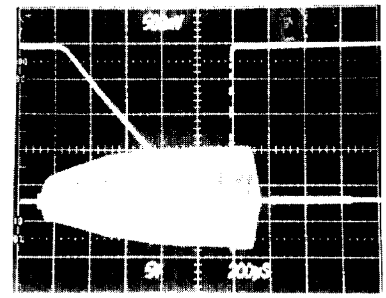


Fig. 3. Accumulation of 3.4x10^{13} ppp.

The kicker modulators operated well in 1985 but deteriorated in 1986, principal problems being failure of the copper sulfate loads and rise-time degradation of the EG&G 5353 thyratrons. The loads are now being replaced by oil-cooled carborundum resistors, and a new high-performance thyratron (EEV 1725) is being evaluated as a replacement tube. The firing of each kicker is separately adjusted (in 1-ns steps) to coincide with the rotation phase of the stored bunch. Timing adjustment is aided by observing the shape of the stored bunch during its last revolution and comparing it with the ejected bunch in the extraction channel.

Beam Diagnostics

The strip-line beam-position monitor (BPM) system, which is tuned to process the 201.25-MHz linac microstructure, has been the diagnostics backbone of both the storage ring and the transport lines. In addition to its use in the transport channels for beam centering, it has been employed to observe fast energy variation at dispersive points, pinpointing linac rf-tuning problems. In the storage ring it is used to measure first-turn position, the closed orbit, betatron tunes, and the amplitude of betatron oscillations from injection errors. Because the system is narrow-band, there is some uncertainty about whether it measures the position of the entire beam stack in PSR or only that of recently accumulated turns. Three detectors are missing from the extraction region because of equipment interferences; the lack of data from these locations leaves open the possibility of an unobserved orbit distortion in that critical part of the ring. A BPM upgrade addressing these problems is now in progress.

Beam-profile diagnostics in the transport lines include wire-scanners, harps, and aluminum oxide viewing screens. In three-unit groups, the harps and wire scanners are used to determine the H^- beam emittance on-line. Measurements of the PSR stored-beam profile are now obtained by kicking the beam into the extraction channel and observing it with a wire scanner or harp. Nonintercepting ionization-type profile monitors are being developed to follow directly the shape evolution of the beam in the ring.

Other diagnostics used in PSR commissioning are beam transformers for measuring the instantaneous stored current and the longitudinal bunch profile, capacitive position pickups that observe beam motion below 100 MHz, and an extensive system of beam-loss monitors. Most of the latter are liquid scintillators coupled to photomultipliers, although vacuum photodiodes have been introduced to provide greater dynamic range for observation of extraction losses. Some of the loss signals are integrated and fed to an automatic loss-limiting beam-abort system. Others are used for turn-by-turn measurement of losses associated with injection, accumulation, and extraction.

Commissioning History

PSR construction was completed on schedule in late March 1985, and first beam was circulated on April 25; initial extraction occurred a month later. The closed orbit was corrected at the start of 1985 (and 1986) operations to within ± 1 mm, using dipole shunts for horizontal adjustment and quadrupole displacement for vertical adjustment. Shortly after turn-on, it became clear that fractional beam losses in PSR were greater than anticipated. After initial debugging of equipment, the bulk of the 8-month 1985 commissioning effort focused on obtaining a clear picture of these losses. Injection optics and processes were studied in detail as an initial key to understanding.

First beam to the LANSCE target occured on September 14. Trial production runs were made in November at 10 µA and then at 30 µA. In December, the first high-intensity experiments were conducted, reaching $2.6 \cdot 10^{13}$ ppp. At charge levels above $1.5 \cdot 10^{13}$ ppp, fast beam loss from (presumed) collective effects was observed.

Activation levels at the end of 1985 were high at the extraction septum (30 R/h). A few points in the injection cell and the two downstream cells (stripper and high-β_x locations) exhibited levels up to 2 R/h, but most of the ring was well below 0.1 R/h.

In 1986, four sextupoles were added to PSR for chromaticity control, the H^0 beam-transmission holes in the injection-cell dipoles were enlarged to reduce loss from the beam halo, and harmonics were added to the rf buncher for homogenizing the longitudinal particle distribution. A wire-scanner/viewing-screen was installed upstream from the septum to provide critical profile information at the entrance to the extraction channel, and the beam-loss monitor system was upgraded to permit quantitative assessment of time-integrated losses around the ring and of the extraction loss.

During the 6-month 1986 running period, PSR operations were divided between LANSCE production (40%), machine development (40%), and maintenance (20%). During much of the PSR maintenance time, beam was delivered to other line-D experimental areas. With more current from the H^- source, a higher stored-charge level ($3.4 \cdot 10^{13}$ ppp) was reached. Activation levels from beam loss in the extraction region were too high to attempt trial operation at 100 µA, originally one of the goals for 1986. Levels at shutdown reached well over 100 R/h at some locations. Extraction aperture and loss measurements in December pinpointed a restriction for the extracted beam caused by an error in the storage-ring vacuum-envelope implementation. Correction of the problem in 1987 is expected to radically reduce extraction losses.

Lattice parameters measured in 1986 (or re-measured with improved accuracy) included the chromaticities, transition gamma, and betatron tunes for the design quadrupole currents. Tune space was surveyed to search for significant resonances in the region near the operating point. Additional studies were performed on beam losses, including the measurement of ring apertures with beam and the dependence of beam lifetime on various machine parameters. Several experiments were aimed at determining the nature of the high-current instability.

In 1986, LANSCE production was at average currents between 10 and 25 µA. Equipment malfunctions in both the storage ring and the accelerator significantly reduced availability in mid-summer, but steady increases in reliability materially improved later operations. Equipment upgrades now under way should provide substantially improved availability in 1987.

Measurements and Results

Betatron Tunes

The PSR design tunes are $Q_x = 3.23$ and $Q_y = 2.21$. These are easily determined with a single strip-line position monitor by injecting one turn and measuring the amplitude of betatron oscillations on successive revolutions. The amplitude-vs-revolution dependence is Fourier-analyzed, yielding the fractional tune. Alternatively, the sidebands of the beam rotational frequency, as seen by capacitive position pickups, can be located directly with a spectrum analyzer. Both methods have been used and agree within $\pm 0.5\%$. The measured tunes agree closely with those predicted from the settings of the F- and D-quadrupole busses over a wide range of adjustment.

Transition Gamma

The lattice transition gamma was determined at the nominal operating tune by measuring the dependence of revolution frequency on the lattice field strength. The field strength of all lattice elements was varied in proportion about the nominal value for the fractional range $-0.010 < \delta B/B < +0.005$. Fitting the frequency-vs-field data with a straight line, and using the differential relation $\delta B/B = \gamma_T^2\ (\delta f/f)$, the measured value of γ_T is 3.22 ± 0.10. This is about 5% higher than the computed value of 3.08.

Chromaticities

The chromaticity for a fixed lattice field and variable beam momentum is defined as $\xi_z = (\delta Q_z/Q)/(\delta p/p)$ with z representing either the horizontal or vertical coordinate. An equivalent definition is $\xi_z = -(\delta Q_z/Q)/(\delta B/B)$, where beam momentum is fixed, but the ring lattice fields are varied. The chromaticities in PSR were measured using both relationships. Figure 4 displays measurements made using B-field variation . A second-order polynomial fit to the data yields the results given in Table I. The differences from the calculated values[3] are significant for both the linear and quadratic terms, suggesting the existence of appreciable nonlinear error fields in the lattice.

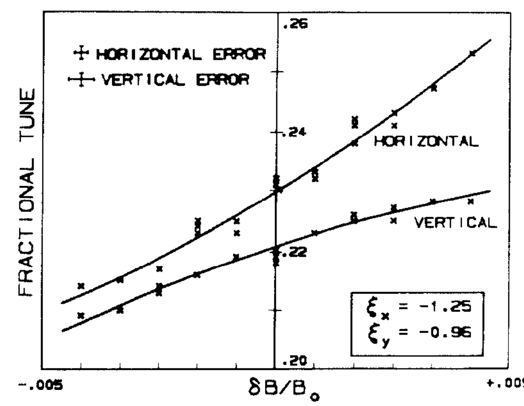


Fig. 4. $\delta Q_x/Q$ and $\delta Q_y/Q$ vs $\delta B/B$ at nominal betatron tunes.

Betatron Resonances

Quadrupole sweeps were used to observe betatron resonances in the half-integer tune-space square containing the PSR operating point. Beam loss at a fixed time after injection was recorded as a function of location on the tune map. It was possible to identify half-, third-, and quarter-integer resonances. Figure 5 shows a Q_x vs Q_y map with resonance lines up to fourth order. The crosses denote measured tune values where beam loss occurs. Resonance lines observed[4] are labelled with their relative strengths. As can be seen, there are no resonances stronger than fourth order close to the PSR working point. The measurements were performed at low beam currents and with the buncher off. No nonlinear lattice elements were activated. The tune-space survey suggests that there are significant nonlinear field errors in PSR, which is in agreement with the chromaticity measurements.

Slow (Scattering) Beam Loss

The measured PSR stored-beam lifetime at low currents is much shorter than expected for the design aperture.[5] During accumulation, beam particles pass

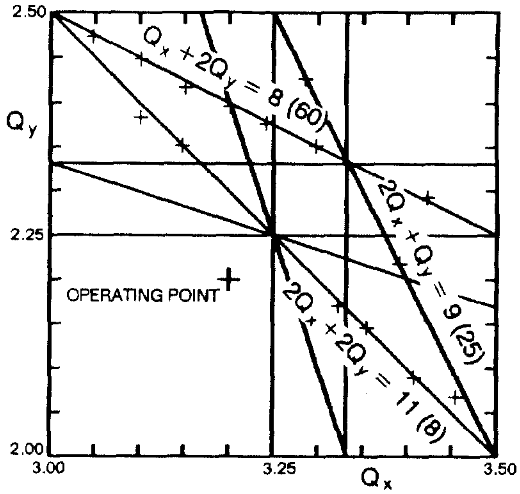


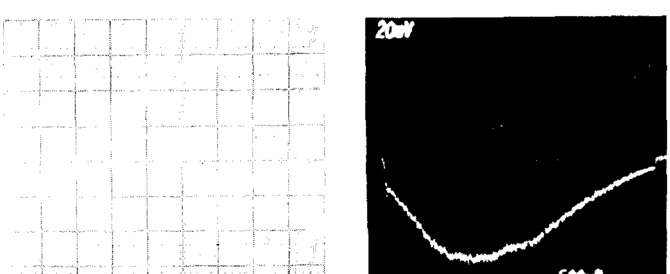
Fig. 5. Resonances near operating point.

repeatedly through the stripper foil. Through Coulomb scattering, the beam size grows according to the relation[6]

$$\sigma_1^2 = \sigma_{01}^2 + \beta_1\beta_s N g \sigma_c \overline{(\delta y')^2} \cdot$$

Here σ_1 is the rms beam size (either x or y), β_s and β_1 are the (x or y) betatron amplitudes at the stripper foil and observation point, N is the average number of collisions with the foil, g is the foil thickness, σ_c is the Coulomb cross section, $\overline{(\delta y')^2}$ is the mean-square scattering angle in each transit , and σ_{01} is the initial beam size at the observation point.

Comparison of the PSR design aperture with the beam size estimated from this formula, even with the protons traversing the foil every revolution, indicates a comfortable margin for standard accumulation times of less than 1000 µs. With a 300-µg/cm^2 stripper, the beam intensity reduction from foil scattering after 1000-µs storage should be less than 1%. However, measurement with such a foil, as seen in Fig. 6(a), shows a much greater reduction (20%). Beam-loss signals from monitors located far from the ring injection cell exhibit the time dependence indicated in Fig. 6(b).



500 µs/div 500 µs/div

Fig. 6. Experiments with a 300-µg/cm^2 stripper foil.
(a) Intensity vs time. (b) Loss vs time.

The dependence of beam lifetime (the time for intensity to drop by 1/e) on stripper thickness was measured. Results appear in Fig. 7 which shows that the lifetime is inversely proportional to stripper thickness. The intensity time dependence is well represented by the expression $I = I_0 \exp(-t/\tau)^{1.7}$ and the loss time-dependence by its derivative. These forms and the observed lifetime dependence on foil thickness are just what would be expected from beam growth caused by foil-scattering, convoluted with a finite aperture. A mechanism removing particles from the beam without an accompanying size increase would have different intensity and loss time-signatures.

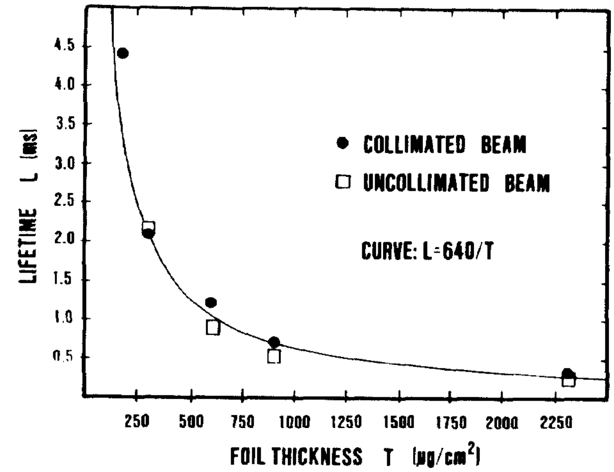


Fig. 7. Lifetime dependence on stripper thickness.

Measurements have shown that the beam lifetime is independent of intensity over several orders of magnitude ($3 \cdot 10^8$ to $5 \cdot 10^{12}$ ppp) and is thus a single particle effect. The lifetime is insensitive to exact choice of operating tune and is unaffected by the storage-ring vacuum. Lifetime increases by a factor of 500 when the beam is moved off the foil by the orbit bumpers.

Removal of circulating protons by nuclear scattering in the stripper foil is a small effect.[7] The beam-intensity reduction from collisions with a 300-µg/cm^2 foil after 1000 µs is about 0.9%. Average energy loss of the stored protons, if they traverse the stripper each turn, would be 1.68 MeV after 1000 µs. Using the maximum lattice dispersion of 2.2 m, the largest orbit displacement would be about 3 mm. Orbit contraction caused by energy-loss thus also seems a small effect.

Lifetime Calculations

Several calculations have been carried out to estimate the beam-intensity time dependence in PSR. Tracking with a linear lattice model and a Monte-Carlo-generated foil-scattering angular distribution[8] produces the results shown in Fig. 8, with horizontal aperture as the scaling parameter. Tracking to third order with MARYLIE,[9] accounting for nonlinear magnet configurational effects and sextupole strength sufficient to produce the measured chromaticity defects, generates small differences from the linear simulation at 4000 µs but none at 1000 µs. Nonlinear simulations were run for only two apertures. Losses calculated using the simple scattering beam-growth model[7] agree with the simulations at 1000 µs.

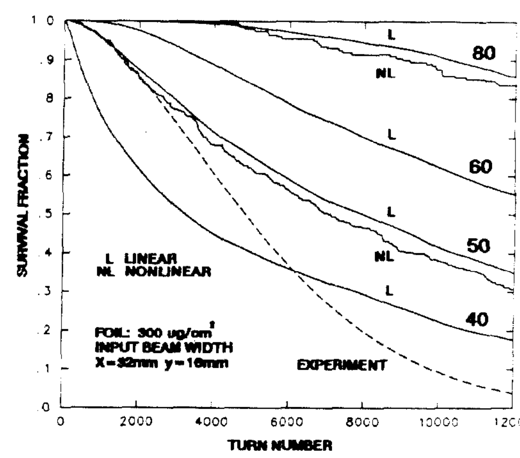


Fig. 8. Beam survival simulations for 300 µg/cm^2 stripper. A = full aperture (in mm) at β_x = 13.0 m.

These calculations, when compared with the experimental beam-survival curve, imply an effective PSR aperture of only 50 mm, rather than the nominal value of 97 mm (at β_{max}).

Physical aperture searches in PSR have turned up no obstructions. An aperture measurement made by expanding the stored beam separately in each plane (with an injection steering error) produced the results shown in Fig. 9. Taken together with a measurement of the beam's full width obtained from adjustable scrapers, these data indicate a 50-mm aperture surplus in the vertical plane but none in the horizontal plane. Cell-by-cell horizontal-plane aperture measurements using adjustable local orbit distortions have confirmed 40-mm aperture margins in every section except the injection section, where the measurements are difficult to perform. Further experiments are planned in 1987 to address the apparent horizontal aperture deficit in PSR, the origin of which is still unclear.

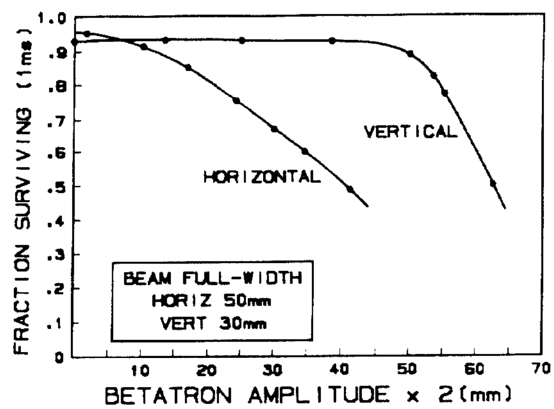


Fig. 9. Aperture measurement with injection steering error.

Transverse Collective Instability

Fast beam loss during accumulation or storage at high charge levels (10^{13} ppp) has been observed in PSR, with typically half the beam vanishing in 50 μs. Figure 10 shows the behavior. Instability occurs when the accumulated current reaches a threshold value that depends on several parameters, including beam cross section, rf amplitude, and the strength of nonlinear lattice elements.[10] The growth rate, as estimated from the beam-loss rate, is much faster than the synchrotron frequency.

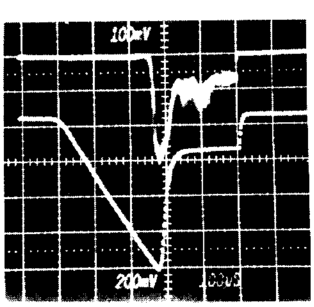
The threshold current increases nearly linearly with increasing rf amplitude. With the rf switched off, the stored beam becomes unstable above $5 \cdot 10^{12}$ ppp, but with the rf amplitude at 13-kV stability can be achieved with nearly ×7 more charge. Presumably, the greater stability is derived from the increased δp/p obtained with a large rf bucket height.

Experiments were performed to assess the effects of sextupoles. Highest s table currents were achieved with a large negative vertical chromaticity (ξ_y = -4.0) and horizontal chromaticity simultaneously positive (ξ_x = 0.5). The dependence on chromaticity was greatly reduced with small δp/p. In a separate experiment performed with octupoles (installed in December 1986), the achievable stable current level increased approximately linearly with octupole strength.

Transverse oscillations (seen on the capacitive pickups) are noticeable shortly before beam loss occurs and continue during beam loss. Spectrum analysis reveals significant betatron sidebands during unstable beam pulses that are not present during stable pulses. A substantial increase in signal power at 30-40 MHz is observable on the position pickups during unstable behavior.

Most of the available evidence indicates that the instability is transverse rather than longitudinal. The exciting transverse impedance is estimated at 10^6 Ω/m and appears to have a high-frequency spectrum (30-100 MHz). The source of the impedance has not been identified, but analysis of existing PSR structures suggests that the orbit-bump magnets may be troublesome.[11]

At the highest charge levels reachable with the existing H^- beam ($3.4 \cdot 10^{13}$ ppp), PSR parameters (beam size and rf amplitude) can be adjust to make the beam stable at least for long enough to complete accumulation and extraction. To reach still higher charge levels, it may be necessary to reduce structure impedances in the ring and to use control elements such as octupoles, sextupoles, or an active damper.



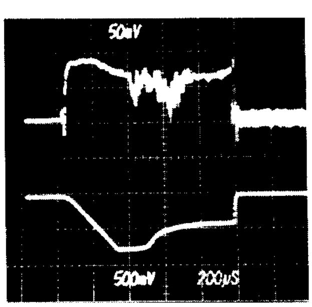


Fig. 10. Top: Beam loss
Bottom: Beam intensity

Top: Vertical position
Bottom: Beam intensity

Acknowledgment

This work is reported on behalf of the entire PSR commissioning team, who have devoted a large fraction of their professional lives in the past two years to bringing this machine into operation. The team, composed of both AT- and MP-Division staff, includes R. A. Hardekopf, A. J. Jason, B. Blind, R. E. Shafer, T. W. Hardek, R. J. Macek, R. D. Ryder, M. A. Plum, J. W. Hurd, H. A. Thiessen, E. P. Colton, D. V. Neuffer, D. Fitzgerald, G. R. Swain, G. A. Sawyer, and P. Clout.

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