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Summary

The Proton Storage Ring (PSR),[1] whose installation was recently completed at Los Alamos, is a fast-cycling high-current accumulator designed to produce intense 800 MeV proton pulses for driving a spallation neutron source.[2] The ring converts long beam pulses from the LAMPF linear accelerator into short bunches well matched to requirements of a high-resolution neutron-scattering materials science program. The initial performance goal for this program is to provide 100-μA average current at the neutron production target within a 12-Hz pulse rate. Project construction began in May 1982, and was completed in mid-April 1985. First beam was circulated in the ring on April 26. Operation at 20 μA is scheduled for September 1985, with full intensity within the next year.

The storage ring was originally designed to function in a second mode in which six 1-ns bunches are accumulated and separately extracted every LAMPF macropulse. Implementation of this mode, which would serve a fast-neutron nuclear-physics program, has been deferred in favor of initial concentration on the neutron-scattering program.

This paper summarizes the PSR design and status. Unique machine features include high peak current, two-step charge-stripping injection, a low-impedance buncher amplifier to counter beam-loading, and a high-repetion-rate strip-line extraction kicker.

General Description

For the materials science mode (long bunch), the PSR was designed to accumulate entire linac macropulses, each 750-μs long and containing 5.2×10^{13} particles, at a repetition rate of 12 Hz. The average current provided to the neutron-production target is thus 100 μA. If stored-beam losses can be sufficiently controlled, the long range plan calls for raising the pulse rate in stages to 48 Hz, and the current to 400 μA. All pulsed beam-handling equipment has been built to operate at up to 24 Hz, providing potential trade offs between pulse-rate and peak accumulated charge.

In the nuclear physics mode (short bunch), which originally dominated planning and set many of the challenging performance requirements, the ring was to accumulate 1×10^{11} protons in each of six 1-ns bunches during the last 110 μs of every linac macro pulse. These bunches were to be individually extracted at 1.4 ms intervals between injection cycles, to provide a pulse rate of 720 Hz at the target.

The top portion of Fig. 1 shows schematically the relationship between the storage ring, the linac, switchyard, existing beamline-D, and the materials science neutron source (and other research areas) served by that beamline. The expanded lower portion is a plan view of the storage ring and the new transfer lines connecting it with Line-D. Because injection into the ring is by charge-stripping, it was necessary to provide a new high current H^- beam at LAMPF and a means for delivering it to Line-D while maintaining existing beam-distribution arrangements for other experimental areas. The extensive modifications to LAMPF engendered by these requirements were a significant part of the PSR project cost and effort. Numerous modifications to Line-D were made as well.

PSR operating mode parameters are given in Table I. Tables II and III list structural and dynamical parameters.

The ring optical design is basically a symmetric 10-cell FODO separated-function lattice. The particle circulation period is 357.7 ns at the design energy of 797.0 MeV. This period was chosen to be 72 × the linac micropulse-spacing of 4.969 ns, allowing accumulation of six equispaced bunches at 59.63-ns intervals in the short-bunch storage mode.

Civil Engineering and Shielding

The storage ring is housed in a 0.5-m-thick concrete tunnel 3.66 m high x 5.49 m wide, which is buried beneath an 8.2-m thick earth berm. With the addition of 0.6 m of steel over anticipated beam-loss points, this berm provides adequate neutron shielding against a several-microampere single-point beam loss.

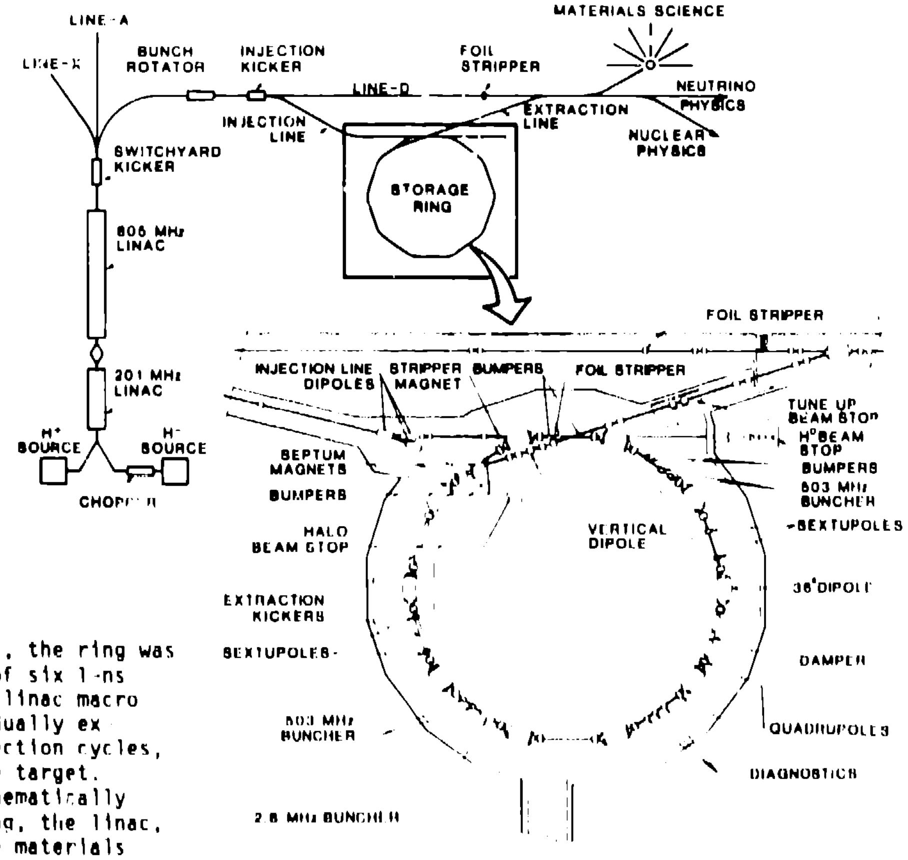

Fig. 1 Top: Relationship between storage ring and connecting facilities (not to scale). Bottom: Plan view of storage ring and beam transfer lines.

The tunnel is large enough to allow local shielding around hot spots such as the extraction septum, and it can also be retrofitted with remote-handling mechanisms should that prove necessary. Despite such conservative design, the intent is to keep total beam losses below 100 nA, which will permit hands-on maintenance of components.

Power supplies, instrumentation electronics, and the controls interface (as well as conventional services) are located in a 27 by 27-m metal building centered on the top of the berm. Connections with the equipment in the tunnel are made through 0.6-m-diam vertical penetrations.

TABLE I

PSR OPERATING MODE CHARACTERISTICS

	Materials Science	Nuclear Physics
Number of bunches	1	6
Bunch length	270 ns	1 ns
Bunch interval	-	59.63 ns
Buncher frequency	2.795 MHz	503.125 MHz
Protons/bunch (max.)	5.2×10^{13}	1×10^{11}
Accumulated turns	2100	300
Injection rate	12 Hz	120 Hz
Filling time	750 μs	110 μs
Extraction rate	12 Hz	720 Hz
Peak current	46.3 A	24.0 A
Average current	100 μA	12 μA

Preparation of the H^- Beam

A new high-current H^- ion source[3] has been developed to supply the 12-mA peak beam needed for charge-stripping injection into PSR. This source delivers a current of 20 mA within a (normalized) emittance of 0.08 π·cm·mrad. A new 750 keV H^- transport system[4] has been implemented to satisfy optical requirements of the high-current beam, to multiplex it with the polarized H^- (P^-) beam, and to provide the desired pulse patterns for PSR and other Line-D experimenter needs.

The 750 keV line includes a unique traveling-wave wideband beam-chopper[5] that generates the 270-ns pulses for stacking in the PSR long-bunch mode. Working with a 16.7-MHz prebuncher, the chopper also permits single-micropulse selection for Line-D or PSR fast-neutron users. The chopper deflector consists of balanced dual helical transmission lines, and is driven by planar-triode amplifiers having 5-ns rise times. The chopper operates at full linac duty factor and interfaces with the PSR controls system through a CAMAC-based pattern generator that sets the desired length, repetition rate, and internal structure of the transmitted beam pulse sequences. To deliver high-current H^- macropulses to Line D without compromising transmission of H^+ beam to Area A and P^- beam to Line-X, it was necessary to completely rebuild the LAMPF switchyard.[6] In the new configuration, which was installed during the recent 6-month shutdown, H^- and H^+ beams are first separated by a 4.5° vertical bend. The H^- beams, which can have different energies, are recombined in a vertical achromat. Pulses for PSR are then kicked 1.15° horizontally into a 4.55° dc septum magnet, the new first element in Line-D, while other pulses pass into Line-X.

The kicker[7] is composed of two identical ferrite-core single-turn pulsed magnets, each driven by a PFN and a highly regulated FET modulator. Pulse outputs are 1 ms at (up to) 24 Hz, or 150 μs at (up to) 120 Hz, with 40-μs rise times, and flat-top variation <0.1%. In the long-bunch mode, entire 750-μs macropulses are switched. In the short-bunch mode, the last 110 μs of every macropulse is switched, the chopper providing a 40-μs gap between macropulse segments. The balance of each macropulse is filled by P^- beam transmitted to Line-X.

Beamline-D has been upgraded by the addition of eight new quadrupoles, to transport the intense H^- beam needed for PSR, optically match the new PSR transfer lines, and contain the high peak current extracted from the ring. Twenty-one strip-line beam-position monitors have been installed to augment existing wire-scanner diagnostics. A foil stripper has been located as shown in Fig. 1 to convert H^- beam to H^+. This stripper is necessary because the magnets downstream have fields strong enough to ionize the H^- beam.

Injection System

H^- beam is transported to PSR through Line-D. The line begins with an 89° horizontal achromatic bend that is followed by an achromatic vertical S-bend (waterfall), lowering the elevation 5.2 m to match the terrain south of the linac. A slow kicker (4-ms rise time) then bends macropulses 1.5° into the PSR injection line. To obtain adequate shielding and to satisfy injection and extraction requirements, the ring is located 3.66 m lower than Line-D, and its center is 22.1 m west. The plane of the injection line (also an achromatic S-bend) is skewed, bending simultaneously in the vertical and horizontal.

A longitudinal rf matching device (bunch rotator) is planned for the empty Line-D segment below the waterfall. This debuncher will be needed for

TABLE II

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 by 28 cm
No. of periods	10	Quadrupole gradients	3.95, -2.35 1/m
Free straight section	4.48 m/cell	Quadrupole aperture	18.1 cm
Dipole length (eff.)	2.55 m	Quadrupole length (eff.)	0.47 m

TABLE III

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 π·cm·mrad
Proton β, γ	0.842, 1.349	Emittance*, extracted beam	2.0 π·cm·mrad
Proton rigidity	4.869 T·m	Phase advance/cell	
Transition γ	3.08	horizontal	116.3°
Tunes (Q_H, Q_V)	3.23, 2.22	vertical	79.9°
Chromaticity (ξ_H, ξ_V)	-0.82, -1.30		

*un normalized

reduction of momentum spread in injected micropulses to ensure 100% longitudinal capture of beam in the PSR at high intensities.

The injection line includes three sets of translatable scraper foils, which are used to convert off-momentum particles and large amplitude transverse beam tails to H^+. The scraped beam is bent oppositely to the H^- at the bottom of the S-bend and directed to a beam dump buried below the ring floor. Beam entering the ring is thus free from halos and momentum tails.

Injection involves a two-stage charge-stripping process. The weakly bound second electron of each H^- ion is first removed by passage through a strong (1.8-T) transverse magnetic field. To minimize angular dispersion, the field gradient must be as high as practical, which implies a narrow gap (1 cm). Transfer-line optics produce a 3-mm diam beam at the magnet location. Efficiency of conversion to H° is predicted to be 100% and the process is accompanied by <1 mrad angular dispersion.[9]. First beam tests show that this neutralization procedure, unique among storage ring injection schemes, works well.

The H° beam enters the ring through a 6-cm hole in the yoke of a 36° dipole, after which it is stripped to H^+ in a 300-µg-thick carbon foil. Stripping efficiency is about 98%. The residual H° beam exits the lattice through a hole in the next downstream dipole and is dumped in a heavily shielded beamstop buried in the tunnel wall. The final optical elements in the injection line are mounted on a remotely adjustable table to align the beam correctly on the foil while maintaining centering in the stripper magnet.

Control of transverse phase-space filling during injection (in both x-x' and y-y' planes) is accomplished by a programmed vertical distortion of the ring's closed orbit as beam is simultaneously swept horizontally by pulsed steering magnets in the injection line. The orbit bump is produced by six single-turn air-core magnets driven by transistorized modulators with transition times of 5 µs.[10]. Typical bump angles are 1 mrad, and maximum orbit distortion at the injection stripper is 10 mm. At the end of injection, the residual orbit bump collapses to zero in a few microseconds, removing the stored beam from additional passages through the foil.

Storage-Ring Physical Structure

All conventional magnets[11] in the PSR project were designed or specified by Los Alamos staff and procured commercially. On the other hand, the kicker magnets (switchyard, injection, and extraction), orbit-bump magnets, the injection stripper and the extraction septa were developed and fabricated in-house.

The ten 36° ring dipoles, whose cores were constructed from 1.5-mm-thick steel laminations, have parameters given in Table II. Laminations were used to ensure close magnet-to-magnet field similarity. The magnets have parallel ends with the laminations staggered to follow the particle orbit curvature.[11] The dipoles were mapped over their working volume with an accuracy of 2×10^{-5} by an integrating coil. With iteratively machined removable pole-end blocks, the magnet effective lengths were adjusted within a tolerance of 1×10^{-4}, and integrated sextupole field errors were reduced below 1×10^{-4} of the dipole field. The 10 dipoles are powered in series by a single supply, with shunts for trimming the current in individual magnets.

The 20 ring quadrupoles were fabricated from solid steel and have 18.1-cm apertures. Higher order multipoles were reduced below 1×10^{-4} by shimming the quadrupole ends.

The vacuum system is conventional, and consists entirely of stainless steel components. Two 400 l/s ion pumps are mounted to each ring straight section. A base operating pressure (without beam) of 5×10^{-9} torr is expected. No special surface treatment is required because the beam storage time is too short for the ion-wall instability to be a problem. Quick-disconnect flanges have been used in anticipated high-activation areas.

Accumulation and Bunching

Two different bunching systems are used to contain the longitudinal motion of the ring bunches in the two operating modes. A conventional single-gap ferrite-loaded 1/4-wave coaxial rf cavity operating at 2.8 MHz (h = 1) is used for confining the beam in the long-bunch mode.[12] Its function is to maintain a 90-ns gap in the circulating beam to facilitate loss-free single-turn extraction. A single buncher unit is needed, with a peak rf amplitude of 14 kV at full beam intensity. The amplitude is ramped during beam accumulation to match the longitudinal space-charge forces. Because of the very large stored beam currents, the buncher amplifier has been designed with an exceptionally low output impedance (20 Ω) to minimize beam loading.

The bunching system for the short-bunch mode consists of four pairs of side-coupled cylindrical TM_{010} cavities operating at h = 180 (503.125 MHz), and driven by two 55-kW UHF television transmitters.[13] Although the transmitters are on hand, and a cavity prototype has been built, implementation of the complete system has been deferred. To compensate for the very large cavity voltage induced by the resonant component of the circulating beam, the tune of each pair of buncher cavities is rapidly adjusted over a 100 kHz range during injection and extraction. This tuning is accomplished by coupling to a rectangular cavity containing YIG ferrite immersed in a rapidly programmed perpendicular-bias magnetic field. Calculations have shown that the system will remain stable with appropriate programming of the buncher resonant frequency (to match the beam current during accumulation and extraction).

Extraction

Beam extraction[14] (which occurs <100 µs after accumulation is completed) is in the horizontal plane and is accomplished by two 4-m-long ferrite-free, balanced strip-transmission-line kickers. These are each driven by thyratron-switched ferrite-isolated Blumlein modulators,[15,16] that deliver 400-ns (60-ns rise time) ±45-kV pulses in the long bunch mode. A second set of modulators is used for the short-bunch mode; these deliver 30-ns-long pulses with 30-ns rise-and-fall times at a rate of 720 Hz. The two kickers sequentially provide 6.5-mrad outward and 5.4-mrad inward deflections, that add because of the 132° betatron phase advance between kicks.

After passing through the D and F quads following the second kick, the deflected beam is 9 cm radially inside the normal orbit and enters the aperture of a 0.5-T dc septum magnet, the first element of the extraction channel. A second septum operating at 1.0-T then directs the beam to a vertical switching dipole that bends the beam either upward into the extraction line or downward to a beam dump below the channel floor. The latter feature allows the PSR to be tuned while uncoupled from the neutron source. The (periodic) extraction line, consisting of 10.2-cm-aperture quadrupole doublets at 6.24 m intervals, rejoins Line D in a skewed 19.4° dipole. Quadrupoles have been retrofitted to Line D between this point and the target to maintain the same focusing-element density. The entire extraction transport line has been optically designed to handle peak beam currents of 46 A with a $\delta p/p$ of ±0.003.

Diagnostics

Diagnostics in the ring presently include a beam-position monitor (BPM) system, current monitors, a quadrupole moment detector, beam-loss monitors, a wideband pickup, and a set of beam-edge feelers. A nonintercepting profile monitor will be added later.

The BPM system,[17] which has also been installed in the injection and extraction lines and in Line-D, consists of 58 4-element strip-line detectors multiplexed into two rf signal processors. In the ring the detectors are placed inside the quadrupoles. The X and Y position processors operate on the 201.25 MHz component of the beam current and convert normalized signal-amplitude differences to phase differences proportional to the beam offset in each detector. The system has a wide dynamic range and a position resolution of about 0.1 mm. A complete picture of the closed orbit can be obtained in 1.4 s. Alternatively, the beam position at a single detector can be read each revolution, a useful feature for tune measurement and for observing development of transverse coherent motion. Position processor output is communicated to the control computer through a dedicated 8085 microprocessor.

Two kinds of current monitors have been installed, beam-current transformers (toroids) and resistive wall-current monitors.

The quadrupole-moment detector is a symmetrical four-element strip-line device identical to a BPM, but its summed X-outputs are subtracted from the summed Y-outputs. This provides a signal proportional to the difference in X and Y beam size.

The edge feelers are foils remotely translatable in the X and Y directions that can be adjusted to intercept the edges of the beam. These provide a measure of the beam size and also can determine the stored-beam halo distribution.

In addition to BPMs and current monitors, the PSR injection and extraction transport lines are fitted with insertable multiwire beam-profile detectors (harps)[18] and TV-readable phosphor screens at several locations.

Controls System

A new controls system[19] has been implemented to operate not only the storage ring and its beam transfer lines, but also the neutron source and beam lines serving adjoining experimental areas. The system is based on a DEC VAX 11/750 computer driving a CAMAC serial highway linking five instrumentation subsystems. These are centered on DEC LSI-11/73 satellite computers, each of which controls and communicates with a separate section of the project through its own local CAMAC serial highway. The central control console contains six 19-in color-graphics touch screens and three panels of four assignable knobs. A layered system of modular software is built around a run-time control database and the VMS and RSX-11S operating systems. Apart from normal analog and digital I/O, the CAMAC system provides timing delays with subnanosecond resolution and analog waveforms to control the orbit bump system, the chopper pattern, and much of the diagnostic instrumentation.

Results and Acknowledgments

Beam was injected into PSR on April 26 after several days of transport system tuning and debugging. It circulated immediately after the ring magnets were set to their design values. Using data from the BPM system, which performed flawlessly, preliminary confirmation of the betatron tunes was made. With the fast current monitors we observed stacking up to about 30 injected turns (3×10^{11} protons) and saw the beam circulate for more than 1000 revolutions.

The commissioning plan thus initiated calls for increasing the current in steps to 20 µA by September 1985, and for reaching full intensity by September 1986.

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References

1. G. Lawrence, R. Cooper, D. Hudgings, G. Spalek, A. Jason, E. Higgins, and R. Gillis, "LASL High Current Proton Storage Ring," Proc. XIth Int. Conf. on High Energy Accelerators, Geneva, July 1980, Experimentia: Suppl. 40, 103 (1981).
2. C. Bowman, "Status Report on the WNR/PSR Pulsed Spallation Neutron Source at the Los Alamos National Laboratory," Proc. Int. Collab. on Adv. Neutron Sources (ICANS-VII), Atomic Energy of Canada Limited Report No.8488, 9, (1984).
3. R. Stevens, Jr., R. York, J. McConnell, and R. Kandarian, "Status of the New High Intensity H⁻ Injector at LAMPF," Proc. 1984 Linac Conf., Gesellschaft fur Schwerionenforschung Report No.GSI-84-11, 226 (1984).
4. H. Butler, A. Browman, D. Hagerman, and M. Jakobson, "New 750 keV H⁻ Beam Transport line for LAMPF," these proceedings.
5. J. Lunsford, and R. Hardekopf, "Pulsed Beam Chopper at LAMPF," IEEE Trans. Nucl. Sci., NS-30, No.4, 2830 (1983).
6. J. Allred, Ed., "Progress at LAMPF, January-December 1984," Los Alamos National Laboratories Report No. LA-10429-PR, 215 (1985).
7. R. Hardekopf, E. Higgins, and J. Lunsford, "Ferrite Kicker Magnet for the LAMPF Switchyard Upgrade," these proceedings.
8. D. Hudgings and A. Jason, "Injection System for the Proton Storage Ring at LASL," Proc. XIth Int. Conf. on High Energy Accelerators, Geneva, July 1980, Experimentia: Suppl. 40, 277 (1981).
9. A. Jason, D. Hudgings, and O. v. Dyck, "Neutralization of H⁻ Beams by Magnetic Stripping," IEEE Trans. Nucl. Sci., NS-28, No.3, 2704 (1981).
10. A. Jason, E. Higgins, and A. Koelle, "The Los Alamos Proton Storage Ring (PSR) Injection Deflector System," IEEE Trans. on Nucl. Sci., NS-30, No.4, 2941 (1983).
11. A. Harvey, "Magnets for the Proton Storage Ring at Los Alamos," Proc. VIIIth Int. Conf. on Magnet Technology, Grenoble, September 1983.
12. T. Hardek, "A Low-Impedance 2.8 MHz Pulsed Bunching System for the Los Alamos Proton Storage Ring," Proc. 16th Power Modulator Symp., Arlington, June 1984, 207.
13. L. Earley, G. Lawrence, and J. Potter, "Rapidly Tuned Buncher Structure for the Los Alamos Proton Storage Ring," IEEE Trans. Nucl. Sci. NS-30, No.4, 3511 (1983).
14. D. Hudgings, and A. Jason, "Los Alamos Proton Storage Ring Extraction System," IEEE Trans. Nucl. Science, NS-28, No.3, 2791 (1981).
15. J. Power, W. Nunnally, K. Rust, J. Samuels, and G. Spalek, "Fast Extraction Modulators for the Los Alamos Proton Storage Ring," Proc. of 4th IEEE Pulsed Power Conf., Albuquerque, June 1983, 263.
16. J. Power, B. Blind, and A. Jason, "The Los Alamos Proton Storage Ring Fast Extraction Kicker System," these proceedings.
17. E. Higgins and F. Wells, "A Beam Position Monitor System for the Proton Storage Ring at LAMPF," IEEE Trans. Nucl. Sci., NS-28, No.3, 2308 (1981).
18. D. Lee, J. Bilskie, D. Brown, and R. Hardekopf, and O. vanDyck "Wide Dynamic Range Beam Profile Monitor," these proceedings.
19. P. Clout, S. Bair, A. Conley, R. Ford, M. Fuka, and N. Greene, "The Proton Storage Ring Control System," IEEE Trans. Nucl. Sci., NS 30, No.4, 2305 (1983).