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LASL HIGH-CURRENT PROTON STORAGE RING*)

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ABSTRACT

The Proton Storage Ring at LAMPF is a high-current accumulator designed to convert long 800-MeV linac pulses into very short high-intensity proton bunches ideally suited to driving a pulsed polyenergetic neutron source. The Ring, authorized for construction at $19 million, will operate in a short-bunch high-frequency mode for fast neutron physics and a long-bunch low-frequency mode for thermal neutron-scattering programs. Unique features of the project include charge-changing injection with initial conversion from H^- to H^0, a high repetition rate fast-risetime extraction kicker, and high-frequency and first-harmonic bunching systems.

1. INTRODUCTION

The LASL Weapons Neutron Research (WNR) facility[1], which has been operational since 1977, is a pulsed polyenergetic neutron source driven by bursts of 800 MeV protons generated by the LAMPF linear accelerator. Each proton produces 15 neutrons by nuclear fragmentation when it passes through a thick tungsten target. The primary spectrum ranges from hundreds of MeV to 100 keV; with hydrogenous material surrounding the target the spectrum can be extended into the thermal and epithermal region (0.01-10 eV). Fast neutrons are used for nuclear physics measurements, whereas slow neutrons are used to study the dynamics and structure of materials. Experimenters at both ends of the spectrum use time-of-flight methods to distinguish neutrons according to energy. To obtain good energy resolution without sacrificing flux, the neutrons must be generated in intense pulses whose lengths are short compared with characteristic flight times. The Proton Storage Ring (PSR) meets this need by acting as a proton accumulator, converting long (100-750 μs) linac pulses unsuitable for driving the neutron source into appropriately short very intense bursts without losing particles in the process. To accomplish this, the Ring operates in two distinct accumulation modes, each independently optimized to provide the desired neutron source pulse structure for nuclear physics and materials research programs.

The PSR has recently received authorization for construction at $19 million and is now in the design stage. It will be located in a buried tunnel adjacent to and below the level of the existing beam line (D) that serves the WNR facility. A plan view of the Ring and tunnel, showing component locations, is given in Fig. 1. Beam enters the Ring from line D, and after accumulation is returned to it and transported to the WNR neutron production target. Connections with line D are made by short sloped beam-transport channels. Above the Ring tunnel and on top of a 4.9-m-thick earth shield a 750-m^2 building houses power supplies and control systems. Also included in the project is a 930-m^2 building for component development and assembly.

2. OPERATING MODES

Operational characteristics of the two PSR storage modes are summarized in Table 1. In the short-bunch high-frequency (SBHF) mode, protons are accumulated in six equally

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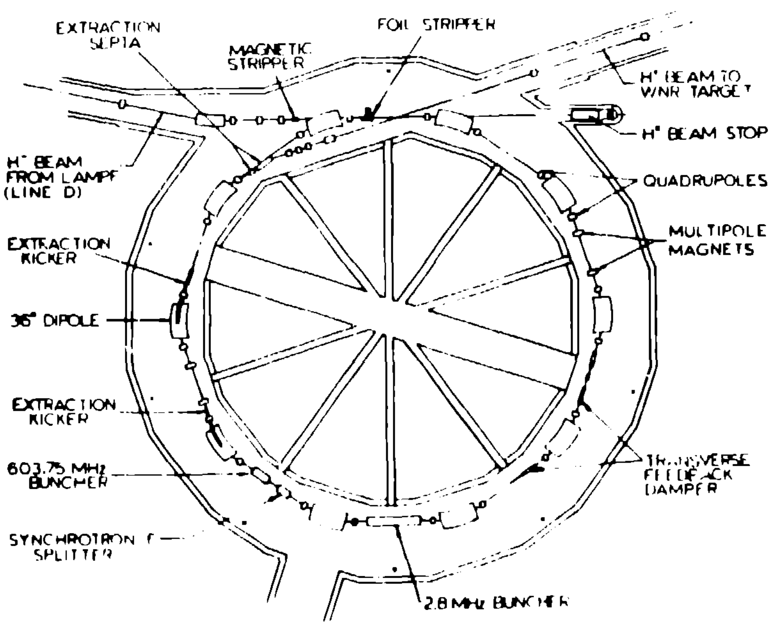

Fig. 1. Plan view of Storage Ring.

spaced 1-ns bunches during each LAMPF beam cycle (macropulse). These are individually extracted by a fast kicker during the 8.2-ms interval between injection periods. Because the linac macropulse frequency is 120 Hz, this produces an extraction rate of 720 pps. The last 108 μs of each macropulse is modified by a chopper-buncher system in the low-energy linac transport to form a sequence of micropulses spaced at 60-ns intervals. The Ring circulation period is chosen such that this injected pulse train is synchronized with the 6 bunches already stored; each incoming micropulse, containing 3.33×10^8 protons, merges with a Ring bunch. Before extraction begins, 300 micropulses are accumulated in each Ring bunch. The narrow bunch width in this mode is maintained by a high-frequency buncher in the Ring.

In the long-bunch low-frequency (LBLF) mode the Ring accumulates entire linac macropulses (5.2×10^{13} protons) in a single 270-ns bunch. Each stored bunch is extracted immediately after completion of the injection cycle, with a maximum delay of 4 ms. Cycle repetition rate is 12/s. Peak current, assuming a parabolic longitudinal charge distribution, is 46.3 A; average circulating current is 100 μA. A slow-wave chopper in the linac low-energy transport carves each macropulse selected for the Ring into a continuous sequences of 270-ns pulses separated by 90-ns intervals. The Ring period is such that entering pulses are phase matched with those already stored. A first-harmonic buncher keeps the 90-ns interval clear of protons to facilitate low loss extraction. After accumulation is complete, the Ring is emptied in a single turn by the fast-extraction kicker.

Table I. PSR Operating Mode Characteristics

	Short Bunch High Frequency	Long Bunch Low Frequency
Utilization	nuclear physics	materials science
Number of bunches in Ring	6	1
Bunch length in Ring	1 ns	270 ns
Bunch interval in Ring	59.63 ns	-
Buncher frequency	603.75 MHz	2.795 MHz
Protons/bunch accumulated	1×10^{11}	5.2×10^{13}
Accumulated turns	300	2100
Injection rate	120 bursts/s	12 pps
Filling time	108 μs	750 μs
Extraction rate	720 pps	12 pps
Peak circulating current	24.0 A	46.3 A
Average current	12 μA	100 μA

Table 2. Structural Parameters

Orbit circumference	90.2 m	Dipole field	1.20 T
Focusing structure	DOFO	Bend radius	4.06 m
Lattice type	separated function	Dipole aperture	10.5 cm x 28 cm
No. of periods	10	Quadrupole gradients	3.76, -2.29 T/m
Free straight section	4.7 m/cell	Quadrupole aperture	11.4 cm
Dipole length	2.55 m	Quadrupole length	0.5 m

Table 3. Dynamical Parameters

Circulation period	357.7 ns	$\Delta p/p$ (injection/extraction)	$\pm$0.001/$\pm$0.003
Proton kinetic E	797.0 MeV	Emittance, injected beam	0.05 cm·mrad
Proton β, 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	117°
Tunes (Q_H, Q_V, nom.)	3.25, 2.25	vertical	81°

3. RING DESIGN

PSR structural parameters are listed in Table 2 and dynamical parameters in Table 3. The present design differs somewhat from an earlier concept[2)] in that the circumference has been increased to 90.2 m, and the periods from 8 to 10. The circumference is dictated by a) the need for a first-harmonic bunch length that is short compared with thermal neutron generation times in the WNR target (1-10 μs); and b) the need for a lattice large enough to provide straight sections for injection, extraction, and bunching, as well as space for future upgrades. A separated-function lattice was chosen to allow a wide tune range and for simplicity of construction. The nominal horizontal and vertical tunes of 3.25 and 2.25 were chosen to decouple vertical and horizontal motions, minimize radial beam size at extraction, and locate the transition energy well above the particle energy. The focusing structure is a perfectly symmetric 10-cell DOFO sequence, which provides many moderate-length straight sections, eliminates structure resonance effects below 4th order, and produces reasonable-amplitude betatron functions.

The natural chromaticity of the lattice is negative (about -0.5) in both planes, which should eliminate the need for sextupoles to suppress the head-tail instability. However, 4 multipole magnets are included in the Ring design, so that sextupole field components can be introduced if required. Figure 2 shows the radial and vertical betatron functions and the off-momentum function η for a single period.

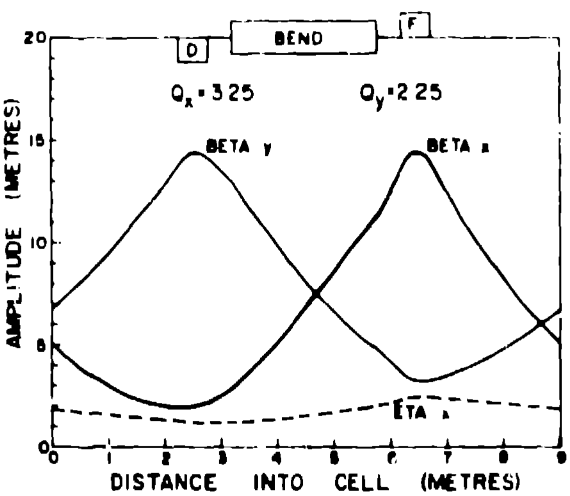

Fig. 2. Radial (x) and vertical (y) betatron functions and off-momentum function for a single period.

The ten 36° dipoles have a 10.5-cm vertical aperture to allow for a large emittance in the LBLF mode, which permits a high space-charge limit. Based on the Laslett expression for the incoherent space-charge limit, assuming a maximum tune shift of 0.2, the acceptance aperture of the Ring would be filled by 4×10^{14} protons in a 270-ns parabolic longitudinal charge distribution. The design goal in the LBLF mode is 5.2×10^{13} protons in such a pulse.

The dipoles will be made from 1.6 mm-thick steel one-piece laminations to insure adequate magnet-to-magnet reproducibility and to minimize random multipole errors. The pole face contour is designed to produce a field uniformity of $\lesssim 5 \times 10^{-4}$ within a 10.5-cm-diam circular section. Pole ends are parallel to simplify lamination stacking.

4. INJECTION

Multiturn injection into the Ring in both operating modes is by charge changing of an intense H^- beam[3]. To provide the required H^- beam intensity and pulse sequences to the PSR with minimum perturbation of other LAMPF experimental areas, some components of the accelerator must be modified. Funds for this are provided in the Ring construction budget. Significant changes include a) installation of a high-current surface-ionization H^- source; b) alteration of the H^- low-energy transport; c) independent steering of H^- and H^+ beams in the linac; and d) reconstruction of the front end of the switchyard. These changes will be accomplished during scheduled LAMPF shutdowns and will be completed by March, 1985.

H^- beam is carried to the PSR from line D by an achromatic transport system. Immediately before the beam enters the Ring it passes through a strong transverse magnetic field (1.8 T) that converts it with 100% efficiency to H^0 atoms[4]. The magnet is specially designed to minimize the angular dispersion accompanying this process. The neutral beam then passes unperturbed through a Ring dipole and subsequently through a thin (~200 $\mu g/cm^2$) carbon foil which converts it to H^+ with 98% efficiency. At this point the incoming particles merge with previously stored protons. A beam stop downstream from the next Ring dipole collects the unstripped H^0 atoms.

The injected H^- beam emittance is 40 times smaller than that of the stored beam at the end of the accumulation cycle. This permits the stored beam phase-space distribution to be arbitrarily adjusted during injection by suitable programming of the relative coordinates of the incoming and circulating beams[3]. Control in the horizontal plane is implemented by a time-dependent closed-orbit distortion near the foil stripper, produced by a 4-element pulsed magnet (bumper) system. Vertical control is accomplished concurrently by pulsed steering magnets in the injection transport line. Figure 3 illustrates the injection scheme.

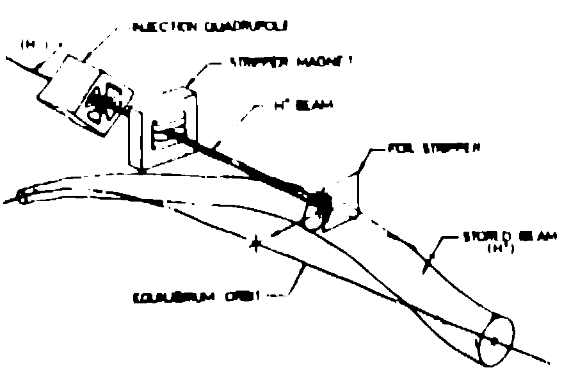

Fig. 3. Injection scheme, showing stripper magnet, foil, and orbit bump.

5. CAPTURE AND BUNCHING

Beam bunches entering the Ring are synchronized in both operating modes to merge with bunches already accumulated. In the SBHF mode, entering bunches will be about 200 ps long and will have a maximum energy variation of ±0.6 MeV. Bunch structure is maintained by a cw bunching system operating at a 603.75-MHz frequency. The buncher cavity is a 2-m-long disk-and-washer structure. A modified TV transmitter package supplies the cavity with up to 100 kW of rf power. Bunching rf amplitude is 1.5 MV. Effects of high beam loading and step-load changes caused by individual extraction of the six stored bunches are handled at extraction time by electronically detuning the cavity and rapidly adjusting the low-level rf drive phase and amplitude[5].

In the LBLF mode the 270-ns-long injected beam bunches are captured by a first-harmonic, 2.795-MHz bunching system. To minimize energy spread during capture, the cavity gap voltage is linearly ramped during the injection cycle to pace the accumulated charge. Maximum rf amplitude and average drive power are 10 kV and 30 kW, respectively. Power is coupled to the beam by a single-gap 2-m-long ferrite-loaded cavity. Because beam loading effects would be severe for a conventional high-output impedance drive, the cavity will be driven by a low-impedance (10 Ω) output stage configured as a power follower. In the SBHF mode, the first-harmonic cavity will be mechanically shorted.

6. EXTRACTION

Beam extraction is in the horizontal plane and is accomplished by two 4 m parallel-plate transmission-line kickers located as shown in Fig. 1. These provide (sequentially) 6.6-mrad radially outward and 3.3-mrad inward deflections that sum because of the betatron phase difference between them. The kicked beam enters the aperture of a 0.5-T dc septum magnet that deflects it into the extraction channel. Radial separation between stored and kicked beams is 10 cm at the septum entrance. Figure 4 displays the beam envelopes of the kicked and unperturbed beams. Extracted beam is conducted to a reinsertion point in line D by a transport system designed for high currents.

The kicker pulse is propagated in a direction opposite to that of the beam to obtain additive deflections from the TEM wave electric and magnetic fields. Pulses are provided by a thyratron-switched ferrite-isolated Blumlein PFN[6]. Rise and fall times are 30 ns in the SBHF mode, with a total base width of 115 ns. These stringent requirements are set by the need to extract individual bunches without disturbing those remaining in the Ring. Pulse amplitudes are ±50 kV, and peak power is 100 MW, with an average power of 4.3 kW. Pulse repetition rate is 720/s. The unusually high rates, coupled with the short transition times, stretch the state-of-the-art in switch tube technology. Long-bunch kicker requirements are not as demanding, because repetition rates are much lower and pulse fall time is not critical. However, a different energy store is required.

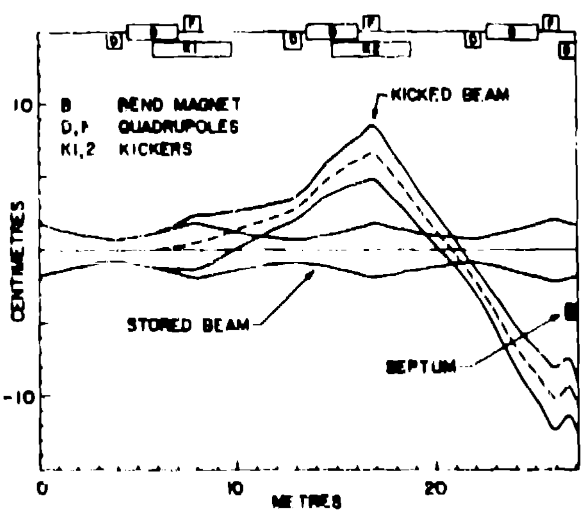

Fig. 4. Beam envelopes of kicked and unperturbed beams in extraction region.

7. INSTABILITIES AND CONTROL

Growth times and thresholds for coherent instabilities in the PSR have been previously investigated by Neil and Cooper[7], and also by Courant, Smith, and Neil[8]. Because of exceptionally high circulating currents, low energy spread, and relatively low energy, PSR operation might appear to be threatened by many instabilities. However, since storage times are short, a few milliseconds at most, only instabilities with growth times of that order are important. This radically improves the situation. Further advantages inherent in the PSR design are a) operation well below transition, which eliminates the negative mass instability, b) a large aperture, and c) good vacuum (~3 x 10^{-9} torr).

The transverse resistive wall instability has submillisecond growth times for the LBLF operating mode. A high-power wideband active damping system is therefore incorporated into the Ring to suppress it. Bandwidth is sufficient for control of growth modes up to n = 20. The system is similar in design to those in use at Fermilab[9]. If necessary the four Ring multipole magnets can be energized as octupoles to raise the threshold for onset of this instability.

The longitudinal resistive wall instability has an n = 1 growth time (LBLF mode) of ~1 s, and would therefore seem to present no problem. However, the local Keil-Schnell criterion applied at the ends of the bunch indicates the possibility of fast-growing instability in these regions. To study the details of longitudinal motion to be expected in the Ring during injection and capture, as well as thereafter, a computer code was written that numerically integrates the Vlasov equation for the appropriate distribution function. The calculation includes longitudinal forces that are due to wall currents and space charge, finite wall resistance, and allows for rf cavities. Details have been presented previously[10]. Figures 5a, b, and c show the calculated PSR long-bunch distribution function: a) as injected each turn; b) halfway through the injection cycle; and c) at completion of injection, after 2100 turns. No evidence of instability appears. The injection process was initiated with the 2.795 MHz rf cavity gap voltage at 2.5 kV; rf amplitude was then linearly ramped to a 10.5-kV final value.

The seriousness of coupled-bunch longitudinal oscillations (SBHF mode) is not known at this time; provision has been made to install a synchrotron-frequency-splitting cavity in the Ring to eliminate this problem should it occur. The Ring is also being constructed to minimize both transverse and longitudinal coupling impedances.

In the SBHF mode the high bunching voltage (1.5 MV) demands a high shunt impedance to keep rf power requirements reasonable. The relatively high beam current (I = 0.53 A at h = 216) thus induces a substantial cavity voltage, and the Robinson instability must be

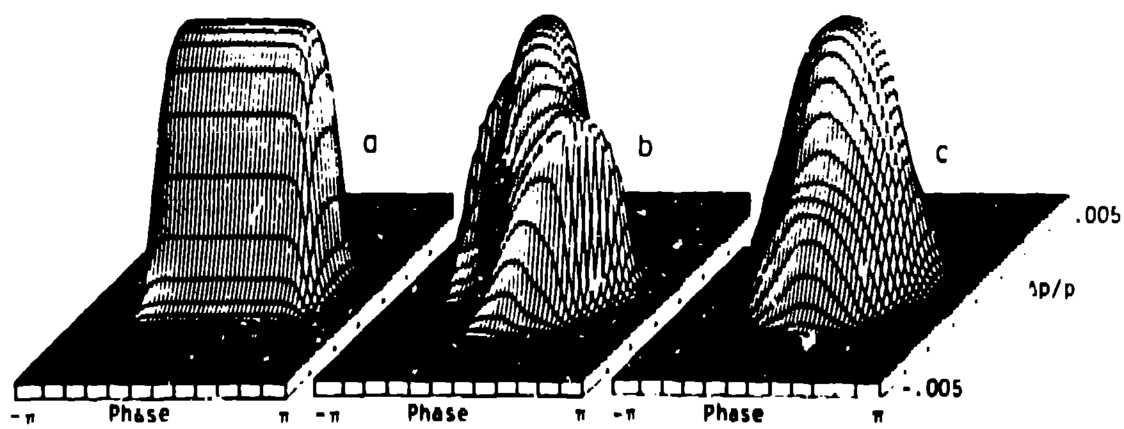

Fig. 5a, b, c. Calculated long-bunch distribution function.
a) injected each turn, b) at 375 μs, 1050 turns, c) at 750 μs, 2100 turns.

considered. The effects of this instability have been calculated[11] and the 603.75-MHz rf system is being designed accordingly.

Two vacuum-related instabilities have also been considered. These are a) beam-induced electron multipactoring[12], and b) the beam-induced ion-wall instability, initially observed in the CERN ISR. The first involves acceleration of electrons into the vacuum wall by the time-dependent radial electric field of the circulating bunched beam. For pulse frequencies and intensities expected in the PSR, calculations suggested that the process could rapidly escalate, leading to pressure rise, diagnostics blinding, and beam loss. However, a simulation experiment indicated that if baked stainless steel surfaces are used in the vacuum system, there should be no multipactoring near PSR bunch frequencies.

The second, the ion-wall instability, is caused by gas evolution from the vacuum walls produced by energetic ions accelerated in the radial electric field of the stored beam. This can also be a rapidly escalating process, leading to pressure rise and beam loss. Detailed calculations for PSR operating modes showed that, because of short storage times, PSR peak currents are at least an order of magnitude below the critical currents for onset of this effect.

* * *

REFERENCES

1) G.J. Russell, P.W. Lisowski, and N.S.P. King, "A Pulsed Spallation Neutron Source at the LASL," Los Alamos Scientific Laboratory report LA-UR-78-2451 (September 1978).

2) R.K. Cooper and G.P. Lawrence, "The Design of the WNR Proton Storage Ring Lattice," IEEE Trans on Nucl Sci, NS-24, p 1037, 1977.

3) D.W. Hudgings and A.J. Jason, "Injection System for the Proton Storage Ring at LASL," Proceedings of this Conference.

4) A.J. Jason and D.W. Hudgings, "The H^- Field Ionization Experiment; Preliminary Results," January, 1980. PSR Tech. Note 45*).

5) M. Donald, "Fundamental Mode Beam Loading in the 603.75 MHz RF System," May 1979. PSR Tech. Note 37*).

6) W.C. Nunnally, D.W. Hudgings, W.J. Sarjeant, "Fast-Extraction Modulators for Los Alamos Scientific Laboratory Proton Storage Ring," Proc of 14th Pulse-Power Modulator Symp., Orlando, Florida, June 1980.

7) V. K. Neil and R. K. Cooper, "Possible Coherent Electromagnetic Effects in the Los Alamos Proton Storage Ring," Lawrence Livermore Laboratory report UCID 16299, (June 4, 1973).

8) Proton Storage Ring Summer Workshop Proc, Los Alamos Scientific Laboratory report LA-6749, UC-28, (October 1977).

9) E. Higgins, Q. Kerns, H. Miller, B. Prichard, R. Stiening, and G. Tool, "The Fermilab Transverse Instability Active Damping System," IEEE Trans on Nucl Sci, NS-22, p 1473 (1975).

10) R. K. Cooper and V. K. Neil, "Proton Accumulator Ring Injection Studies," Proc. of the X Int Conf on High Energy Accelerators, Vol II p 294, Protvino, USSR, July 1977.

11) R. K. Cooper and P. L. Morton, "RF Stability for the PSR," May 1979. PSR Tech. Note 17*).

12) O. Gröbner, "Bunch Induced Multipactoring," Proc of the X Int Conf on High Energy Accelerators, Vol II, p 277, Protvino, USSR, July 1977.

*)PSR Technical Notes are available on request from Group AT-3, MS 808, LASL.