TRANSVERSE COLLECTIVE INSTABILITY IN THE PSR

E. P. Colton, D. Neuffer, G. Swain,
H. A. Thiessen, A. Lombardi†, and T.-S. Wang
Los Alamos National Laboratory

Abstract

An instability in the proton storage ring (PSR) is observed as fast loss of beam during accumulation and storage when the injected beam current exceeds a threshold value. Instabilities are observed during both coasting-beam and bunched-beam operation. Large coherent transverse oscillations occur prior to and during the beam loss. The growth times are rapid, typically in the range 10–100 μs. The instability threshold is observed to depend strongly upon rf voltage, beam size, injected momentum spread and nonlinear fields. Weaker dependences upon betatron tune, vacuum pressure, and stripping-foil bias voltage have also been observed. A possible *e-p* oscillation component of the unbunched beam instability is suggested. Growth times suggest a significant $Re(Z_\perp)$ of ~0.2–0.5 MΩ/m; the source of this is not yet precisely identified.

Introduction

In this paper, we describe the current status and understanding of collective transverse instabilities observed in the Los Alamos Proton Storage Ring (PSR) at high intensities.[1] The PSR was designed to provide 100-μA average current at 12 Hz, which implies accumulating 5.2×10^{13} protons from a ~1 ms linac pulse (sample PSR parameters are shown in Table I). Storage of high-intensity beam has been limited by an instability which appears when more than $\sim 1.5 \times 10^{13}$ particles are stored with bunched beam and when $\sim 0.5 \times 10^{13}$ are stored in unbunched mode, and causes beam loss on a time scale of ~10–100 μs. The instability is accompanied by transverse oscillations at ~ 100 MHz. Figure 1 shows beam loss caused by instability and the accompanying transverse oscillations. More detailed measurements are reported below.

Table I. PSR Parameters.

Proton kinetic energy	T	797 MeV
Circumference	$2\pi R$	90.2 m
Average beam-pipe radius	b	0.05 m
Betatron tune	ν_x, ν_y	3.2, 2,2
Transition gamma	γ_T	3.1
Betatron amplitudes	$\beta_{\min}, \beta_{\max}$	2.0 m, 14.2 m
Dispersion	$\eta_{\min}, \eta_{\max}$	1.1 m, 2.5 m
Chromaticities (measured)	ξ_x, ξ_y	−1.3, −1.0
Buncher harmonic, frequency	h, f	1, 2.795 MHz
Design peak rf voltage	V	15 kV
Maximum synchrotron tune	ν_s	0.0006
Design stored beam	$N_{\max}$	5.2×10^{13}
Design peak current	$I_{\max} = 2\overline{I}$	46.3 A
Maximum stored beam	N	4.0×10^{13}
Filling time	T_0	<975 μs

† present address: Laboratori Nazionali di Legnaro, Legnaro, Italy.

Instability Thresholds

The PSR normally operates with a single 2.8-MHz bunch, and the unstable oscillations are at much high frequencies. The threshold for an impedance-driven instability would be:

$$|Z_\perp| < \left|\frac{4FE_0\beta_\gamma}{e\beta_\perp}\right| \Delta\nu \quad , \tag{1}$$

where I is the peak current, $Z_\perp$ is the transverse impedance, F is a factor of order unity, E_0 is the rest energy, $\beta_\perp$ is the mean betatron amplitude, and $\Delta\nu$ is the tune spread.

Well above threshold the growth rate is

$$\tau^{-1} \simeq \frac{ef_0 I\beta_\perp Re(Z_\perp)}{2\beta_\gamma E_0} \quad . \tag{2}$$

The PSR is a space-charge dominated machine and the space charge impedance is:

$$Z_\perp = \frac{iRZ_0}{\beta^2\gamma^3}\left[\frac{1}{a^2} - \frac{1}{b^2}\right] \quad , \tag{3}$$

where a is the beam radius and b is the pipe size. This is $\sim i10$ MΩ/m, and the PSR operates above the threshold of Eq. (1). The observed growth rate must be driven by a real impedance, and a growth time of 10–100 μs at I = 10 A implies $Re(Z_\perp) >$ 1.6–0.16 MΩ/m. We have been unable to identify a conventional impedance which can be associated with the faster growth rates.

Properties of the Instability

In 1986, a series of experiments exploring the instability showed strong dependences of the threshold on rf-buncher voltages, momentum spread, sextupole and octupole strengths, as well as beam size.[1]

The rf voltage increases the momentum spread, thereby increasing Landau damping for any instabilities. It also forms the beam into a confined bunch, maintaining a beamless gap which can clear trapped electrons. Increasing rf voltages from ~0 to 12 kV increases stable stored beam from ~0.5 to 1.5×10^{13} protons.

Increasing sextupole strengths increases the tune-spread and Landau damping for transverse motion. Optimum strengths place the vertical sextupoles at maximum (−20 A) and the horizontal sextupoles at half strength (10 A), so that the chromaticities are: $\xi_y \cong -5$, $\xi_x \cong 0$. The same optima are found for bunched and unbunched beam. The vertical tune spread is then maximized, confirming BPM observations that the dominant instability is vertical. Increasing octupole strengths also increases tune spread, and improves stability. Figure 2 displays some results of PSR experiments.

The vertical beam size can be increased by steering the injected H^0 beam off the stripping-foil center. Increased beam size reduces the space charge impedance [Eq. (3)] and increases tune spread and also reduces the electron/ion trapping potential. Empirically, larger beam is more stable, and the improvement is more marked with unbunched beam.

A dependence of stable current upon vertical tune has also been observed. The stable current is less when the tune is decreased below the integer.[2]

Investigations of Electron-Proton Driven Instabilities

Experience at other accelerators and comparisons with the PSR data have suggested the possibility of an electron- or ion-driven transverse instability. The instability requires a source of electrons (or ions) which must then be trapped within the beam potential well. Interaction between the beam and trapped electrons can cause unstable oscillations.[3]

The PSR stripping foil, beam-gas collisions, and beam-halo—wall interactions can all produce electrons. The beam space-charge potential is large enough to trap electrons with energies in the 0–100-eV range in unbunched operation. With bunched beam, however, a large beamless gap (~100 ns) is maintained and would pass through the electrons on every turn. The gap is sufficient to clear electrons. The electrons will not be trapped, and are not stably held in the beam-gap oscillations.

However, with unbunched beam, electrons can be trapped stably, even with large beam-density fluctuations. These electrons affect the proton beam dynamics. They cause a tune shift directly opposing the space charge tune shift $\Delta\nu_{sc}$

$$\Delta\nu_e = \frac{N_p r_p R}{\pi b(a+b)\nu\beta^2\gamma}\,\eta = -\Delta\nu_{sc}\gamma^2\eta \quad , \tag{4}$$

where η is the neutralization factor ($\eta < 1$), ($\gamma = 1.85$, $\beta = 0.84$) are the proton kinetic factors, and ν is the tune (2.25 at PSR). Since γ is not far from unity, $\Delta\nu_e$ is not large at PSR parameters.

A more important effect in the PSR should be coupled transverse oscillation of the proton and the electrons. A linearized analysis of these coupled oscillations obtains the resulting dispersion relation, similar to the plasma physics "two-stream" instability:[3]

$$(x^2 - Q_e^2)[(n-x) - \nu^2 + Q_e^2)] = Q_e^2 Q_p^2 \quad , \tag{5}$$

where

$$Q_e = \sqrt{\frac{2N_p r_e R}{\pi b(a+b)\beta^2}}$$

is the electron oscillation frequency (in units of the revolution frequency) and x is the coupled oscillation frequency. Instability can occur at frequencies near $Q_e + \nu$ at relatively small neutralizations (2–10%), and the growth rates can be quite fast (3–10 μs).

Some observations at the PSR are consistent with an *e-p* source of unbunched beam instability.

1. Instability is accompanied by ~60–80 MHz transverse oscillations [$\simeq(Q_e+\nu)f_0$], and the fast growth rates are consistent with those possible with the *e-p* two-stream instability.

2. An experiment in which a voltage was placed on the foil (300 V), sufficient to clear electrons in the vicinity, increased the instability threshold by ~10%. However, the smallness of the improvement does indicate that the instability is not dominated by electrons from the foil that are trapped in its vicinity. In another experiment, background gas pressure was increased from ~10^{-7} Torr to 2×10^{-6} Torr and the instability appeared earlier. However, with rf on, changing the foil and spoiling the vacuum had little effect on the bunched beam instability.

3. In another experiment, the beam was injected bunched with rf on, and the rf was switched off in storage. Instability occurred ~250 μs later, which is approximately a debunching time later. Figure 3 shows the instability developing after the rf is turned off.

While the studies and calculations indicate an *e-p* component of the unbunched-beam instability, the bunched-beam instability source is not known. Further studies are indicated.

High Intensity Operation

At the end of the 1988 run, new records in maximum stable stored and extracted beam were established in an optimization run. At usual operating parameters, a beam of 1.5×10^{13} protons is stable for $\gtrsim 500$ μs after injection with $V_{rf} = 9$ kV.

Increasing V_{rf} to 11.5 kV, adding a second-harmonic rf voltage of 4 kV, optimizing rf phases, and resteering beam injection and closed orbit increased stable beam to 2.5×10^{13}. Increasing sextupole strengths to obtain a maximal negative vertical chromaticity of $\xi_y = -4.5$ and a slightly negative horizontal chromaticity increased stable beam to 3.2×10^{13}. Adding a small octupole field and readjustment of the tunes to $\nu_x = 3.18$, $\nu_y = 2.19$ increased stable beam to 3.6×10^{13}.

Direct extraction after accumulation obtains $\gtrsim 4.0 \times 10^{13}$ protons. The exercise demonstrated that the current goal of 3×10^{13}/pulse can be reached by manipulation of the existing PSR parameters, even without a definitive cure of the bunched-beam instability. Slow losses in this development run were an order of magnitude too large for routine operation. However, the planned injector upgrade (H^- injection) and improved collimation may make this intensity usable.

Search for Impedance Devices

Searches for a possible impedance source or sources which could drive the observed instability have so far been unsuccessful. The orbit bumpers were removed without effect, and the rf cavity was shorted without changing the coasting-beam instability. Measurements of PSR component impedances have not obtained any sufficiently large resistive impedance.[4] The PSR beam position-monitor impedances are in close agreement with calculated values. However, the impedance of the largest devices, the PSR extraction kickers, has not been measured and may be large enough to drive the bunched-beam instability.

References

1. D. Neuffer et al., *Particle Accelerators* **23**, 133 (1988).
2. T.-S. Wang et al., Proceedings 1989 IEEE Particle Accelerator Conference.
3. E. Keil and B. Zotter, "Landau Damping of Coupled Electron-Proton Oscillations," CERN-ISR-TH/71-58 (1971).
4. L. S. Walling, D. E. McMurray, D. Neuffer, and H. A. Thiessen, "Transmission Line Impedance Measurement for an Advanced Hadron Facility," LA-UR-88-3533, submitted to *Nucl. Inst. and Meth.* (1988).

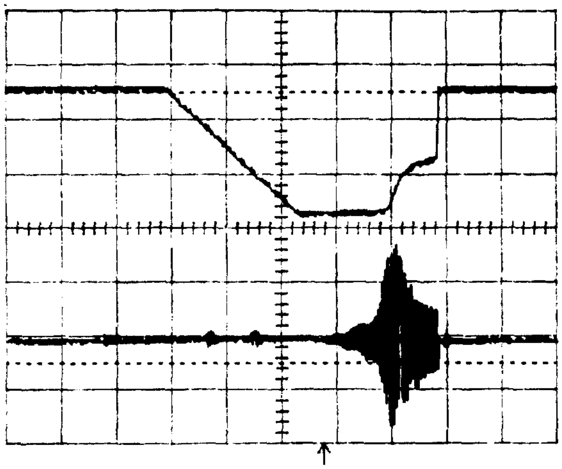
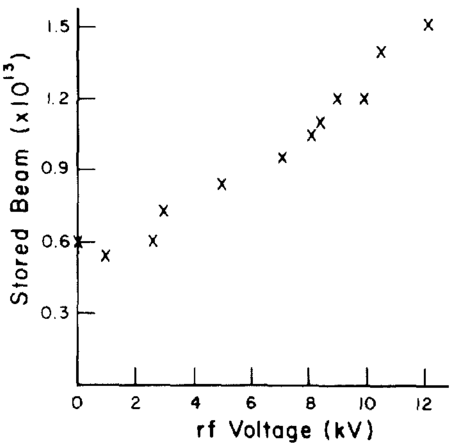
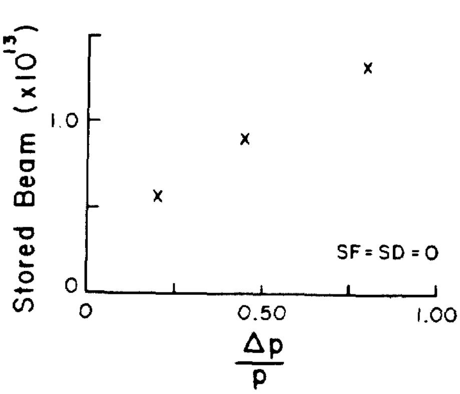
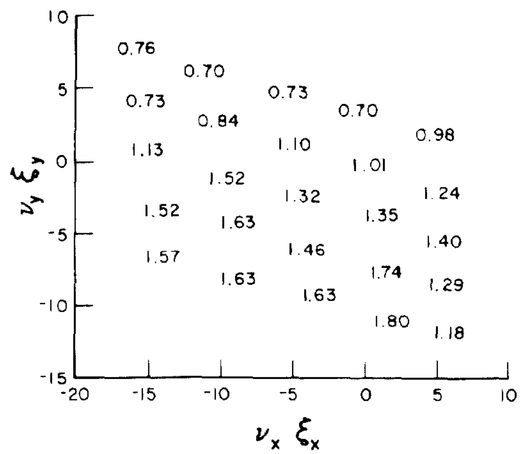


Figure 1. Beam current as a function of time and vertical beam position monitor signals in the PSR. Note the growth of vertical oscillations followed by beam loss.







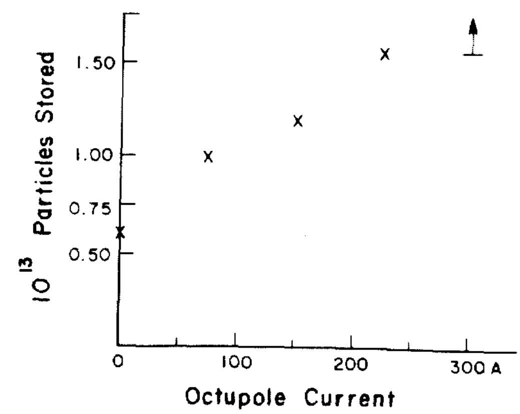


Figure 2. Dependence of maximum stable beam upon various PSR parameters:

(a) dependence upon buncher voltage
(b) dependence upon injected beam momentum spread $\Delta p/p$ (%)
(c) dependence upon horizontal and vertical chromaticities as controlled by PSR sextupoles
(d) dependence upon octupole strength

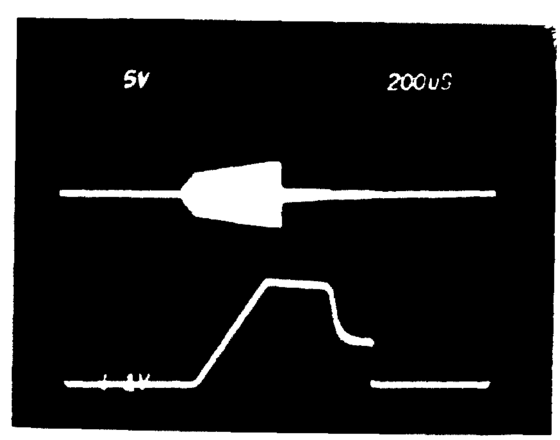


Figure 3. Development of instability with rf buncher switched off during storage. The upper trace is the rf voltage; the lower trace is the stored current.