Observations of the PSR Transverse Instability*

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Abstract

A fast instability with beam loss is observed in the Los Alamos Proton Storage Ring (PSR) when the injected beam current exceeds thresholds, with both bunched and unbunched beams. Large coherent transverse oscillations occur before and during beam loss. Recent observations of the instability indicate that it is an "e-p"-type instability, driven by coupled oscillations due to electrons trapped within the proton beam.

I. INTRODUCTION

The PSR is a fast-cycling, high-current storage ring designed to accumulate beam over a macropulse of the LAMPF linac ($\sim$ 1 ms) by multiturn injection through a stripper foil, and compress that beam into a short, single-turn extracted pulse ($\sim$ 0.25μs). Key PSR parameters include beam kinetic energy T = 797 Mev; circumference $2\pi R$ = 90.1 m; revolution frequency $\Omega/2\pi$ = 2.795 MHz; betatron tunes $Q_x, Q_y \approx 3.17, 2.13$; and current operating intensity $N \approx 2.35 \times 10^{13}$ particles. The design intensity is 100 μA on target at 12 Hz, which implies $5.2 \cdot 10^{13}$ protons/pulse. Average and peak intensities have been somewhat less (80 μA at 20 Hz in 1990, and $4 \cdot 10^{13}$ maximum pulse size). The average current has been limited by slow beam losses, and individual pulse intensities are limited by the fast instability.

The instability appears when more than $\sim 1.5 \times 10^{13}$ protons are stored in bunched mode (rf on) and when more than $\sim 0.5 \cdot 10^{13}$ are stored in unbunched mode. Transverse oscillations at $\sim$100 MHz are seen, and grow exponentially at time scales of 10-100 μs, causing beam losses (see Fig. 1). Initial experiments and observations of the instability reported by Neuffer et al. [1] showed dependences of the thresholds on rf voltage, beam size, momentum spread, and sextupole and octupole strengths. Impedance couplings were suspected to be the cause of the instability. Searches for a possible impedance source were unsuccessful, and recent observations (both with unbunched and with bunched beam) are not consistent with a hardware impedance source. The observations are consistent with the possibility that the instability is an e-p instability, and supporting calculations have shown that conditions for e-p instability may occur with bunched beam in the PSR [2,3].

In an e-p instability, background low-energy electrons are trapped within the space-charge potential of the circulating proton beam. Coupled transverse oscillations of the beam due to the trapped electrons develop, leading to beam losses. The instability has been seen in the Bevatron and CERN ISR, and simple, linearized theoretical models have been developed [4,5]. The equations for the coupled vertical motions of the protons and electrons within the beams are:

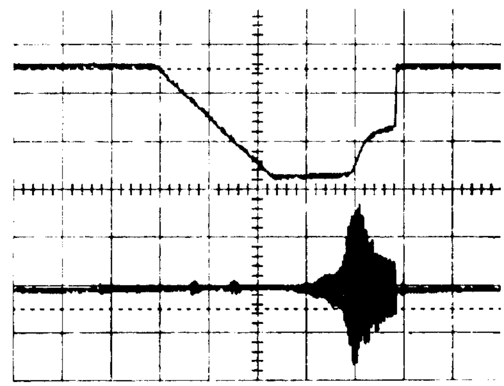

Fig. 1. Beam current (upper trace) and vertical difference signals (lower trace) under unstable conditions.

$$\ddot{y}_p + (Q_y^2 + Q_p^2)\Omega^2 y_p = Q_p^2 \Omega^2 \bar{y}_e \quad ,$$

and

$$\ddot{y}_e + Q_e^2 \Omega^2 y_e = Q_e^2 \Omega^2 \bar{y}_p \quad ,$$

where $Q_e\Omega \cong \sqrt{\frac{2N r_e c^2 (1-\eta_e)}{\pi b(a+b)R}}$, and $Q_p\Omega = \sqrt{\frac{2\eta_e N r_p c^2}{\pi b(a+b)\gamma R}}$.

The motions are coupled through the center of mass $\bar{y}_e$, $\bar{y}_p$ oscillations. Assuming harmonic motion obtains the dispersion relation.

$$(Q_e^2 - x^2)(Q_y^2 + Q_p^2 - (n-x)^2) = Q_e^2 Q_p^2 \quad ,$$

where $x = \omega/\Omega$ is the oscillation frequency in terms of the revolution frequency. For PSR parameters, $Q_e \cong$ 40 ($\sim$100 MHz). The dispersion relation has complex solutions (instability) near $x \approx Q_e \approx n - Q_y$, provided Q_p is large enough. For the PSR, this means $Q_p > 0.1$, which implies that a neutralization of $\eta_e > 0.01$ (1%) can lead to instability at a relatively low electron density. Some stabilization by Landau damping (frequency spread) is possible; the stabilization effects seen in the PSR are qualitatively in agreement with the e-p model.

For an e-p instability to exist, stable trapping of electrons must occur within the space-charge potential of the circulating protons. With unbunched beam, the space charge is quite strong and should easily trap electrons. With bunched beam, a beam-free interbunch gap of $\sim$100 ns should pass through the electrons every turn, freeing rather than trapping electrons. However, recent

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calculations [2] have shown that if a low-density beam having a smooth overall density distribution, leaks into the gap, electron trapping can occur with bunched beam at PSR parameters. Recent experiments (see Section II) do show that the instability is associated with beam leakage, and that such leakage is a plausible result of the PSR longitudinal dynamics, involving rf voltage (relatively small effect), longitudinal space charge (large effect), and injection phase-space mismatch (large effect).

II. Recent PSR Experiments

The results of these experiments are reported in detail in a forthcoming article [3]; we summarize some critical observations below.

A. Background Charge Experiments

An e-p instability depends on a source of electrons that can be trapped within the circulating proton beam. Possible sources include secondaries from beam-foil interactions, beam-gas interactions, and beam losses on the walls. Both beam-foil interactions and beam losses are relatively large in the PSR. Also, there are no clearing electrodes to remove charges. In some recent experiments, PSR background charge conditions have been modified, leading to changes in instability thresholds. Such changes are not consistent with a $Z_{\perp}$-instability, which should be independent of background.

In one experiment, sufficient voltage was placed on the foil to clear electrons in the vicinity. With unbunched beam, an increase to 300 V (the expected space-charge potential) increased thresholds by ~10%; but further increases (to 2000 V) showed no further improvement. In several experiments, the vacuum was degraded from ~2-5 10^{-8} up to 10^{-6} Torr. The beam, bunched or unbunched, became more unstable; thresholds were changed by ~10%. The further instability could be caused by increased e^{-}-density from the beam-gas scattering. In another experiment, beam losses were increased by moving the halo scrapers toward the beam. The beam again became more unstable, even though intensity was decreased. The model is that losses increased secondary e^{-} production, leading to increased instability. That changes in e^{-} density does change the stability of the proton beam is consistent with the e-p instability hypothesis; however, a dominant e^{-} source has not yet been identified.

B. Gap Filling and Instability

Calculations show that bunched beam e-p instability should not occur in the PSR, unless the interbunch gap has filled in. Recent experiments do indeed show that instability only occurs when the interbunch gap has filled in, providing a continuous trapping force for low-energy electrons. In one experiment, beam was injected with rf on, forming a stable bunch. During storage the rf was turned off, and it was observed that as gap-filling proceeded, the beam became unstable.

With bunched beam (rf on), it has generally been observed that instability occurs *only* when the interbunch gap has filled in to some extent. Figure 2 shows bunch shapes in cases slightly below and slightly above threshold, at $V_{rf} = 10\ kV$. In the unstable case, the interbunch gap has filled in, forming a smooth, sinusoidal density variation. Figure 3 shows some longitudinal beam profiles at end of injection. All cases with beam leakage showed strong instability, and all cases with a beam-free interbunch gap were stable.

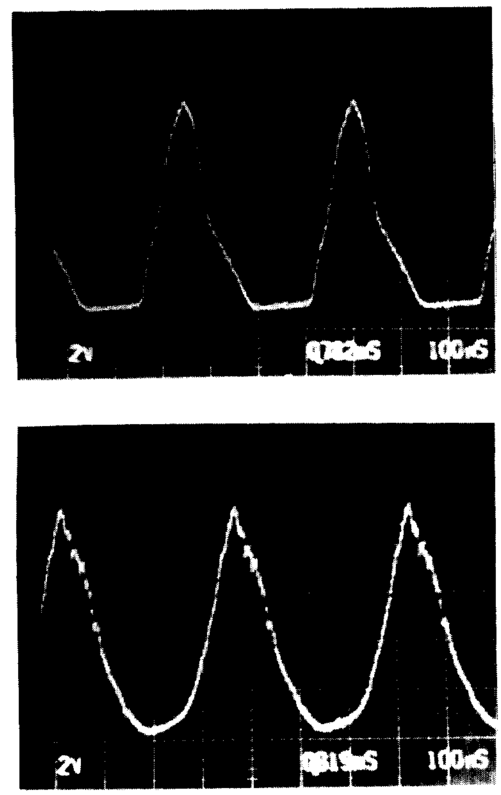

Fig. 2. Beam profiles below and above instability threshold. Note smoothly-filled gap in unstable case.

Measurements under various conditions indicate that gap filling occurs before or simultaneously with the beginning of exponentially growing oscillations, well before beam loss. This indicates that gap-filling is a cause, not a result, of the instability.

In addition, experiments were performed in which a small amount of beam was deliberately injected into the interbunch gap (by degrading injection chopping). The beam became more unstable; instability thresholds were reduced by ~20%. In a complementary experiment, beam was kicked out of the interbunch gap during storage (by a gated transverse kick); the beam was stabilized. Injection can also be modified to make leakage more difficult, by injecting with a shorter width. The beam is then injected deeper into the confining rf bucket. Results show that much more stable beam can be stored by this method.

C. Frequency Spectra Observations

The frequency spectra of the unstable vertical oscillations have been measured by an HP spectrum analyzer and by Fourier transforms of digitized, position-monitor data. Oscillation peaks near 100 MHz with 10-50-MHz widths occur with instability; however, the peak location can vary between 40 and 200 MHz, depending on beam conditions. This is inconsistent with a $Z_{\perp}$ instability, in which the oscillation frequencies should remain unchanged. However, in an e-p instability, the frequencies should be near $Q_e f_0$, and should vary with beam density $\{Q_e f_0 \propto \sqrt{(N'/b(a+b))}\}$. The variations in peak location and width that we observed are consistent with the measured and expected variations in three-dimensional beam density.

III. Summary and Discussion

Recent experiments and calculations indicate that the PSR transverse instability is an e-p instability. Because electron trapping, which triggers the instability, occurs only when there is some leakage of beam into the gap, maintaining a beam-free interbunch gap is desirable in PSR operations. Leakage can be avoided or delayed by manipulating PSR parameters, such as injection width, rf voltage, and phase; such measures have empirically improved operation and assisted in increasing intensity to current levels.

Future experiments will search for more definite proof of e-p instability. A critical experiment would be to investigate more fully the use of a transverse kicker to remove beam from the interbunch gap, to determine whether gap clearing consistently stabilizes the beam. Other experiments should try to identify a dominant e^- source (possibly stripper foil or beam losses); this could point the way for installation of clearing electrodes.

IV. References

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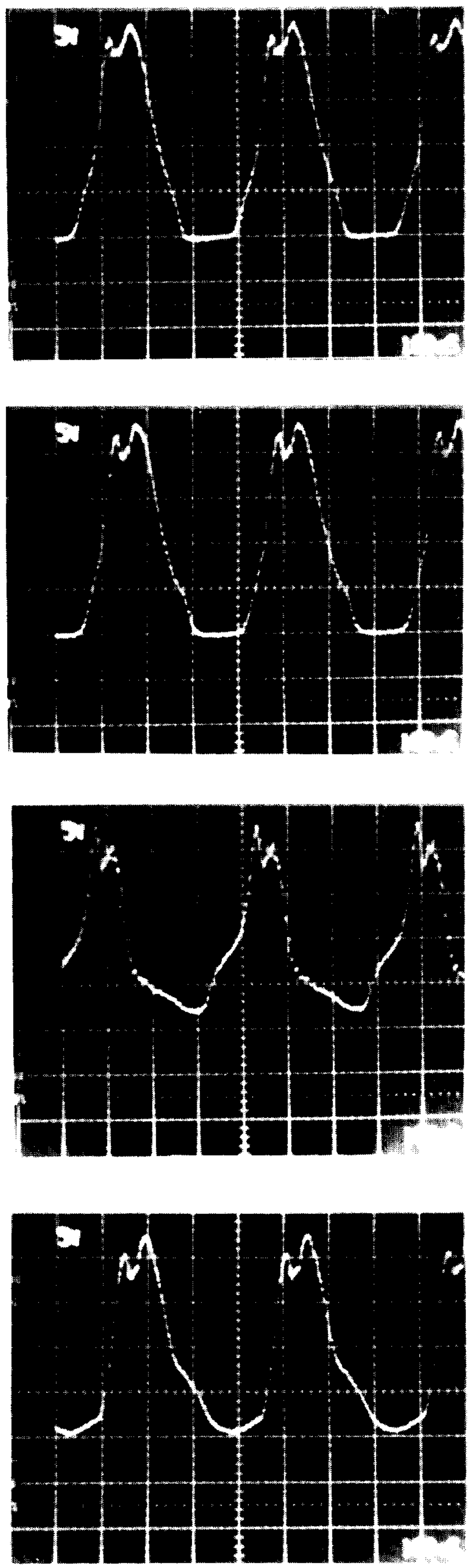

Fig. 3. Beam profiles at end of injection under stable (upper two) and under unstable (lower two) conditions.