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Author(s):
Tai-Sen F. Wang, AT-7
Richard Cooper, AT-7
Daniel Fitzgerald, MP-5
Stephanie Frankle, MP-5
Thomas Hardek, MP-5
Richard Hutson, MP-5
Robert Macek, MP-DO
Chihiro Ohmori, MP-DO
Michael Plum, MP-5
Henry Thiessen, MP-14
Carol Wilkinson, MP-5
Eugen Colton, DOE
David Neuffer, CEBAF
Grahame Rees, RAL

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RECENT STUDY OF BEAM STABILITY IN THE PSR*

T. Wang, R. Cooper, D. Fitzgerald, S. Frankle, T. Hardek, R. Hutson
R. Macek, C. Ohmori, M. Plum, H. Thiessen, C. Wilkinson
E. Colton,† D. Neuffer,‡ and G. Rees*

Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Abstract

A fast transverse instability with beam loss has been observed in the 800 MeV Los Alamos Proton Storage Ring (PSR) when the injected beam intensity reaches 2 - 4×10^{13} protons per pulse. Previous observations indicate that the instability is most likely driven by electrons trapped within the proton beam. Theoretical study has shown that beam leakage into the inter-bunch gap leads to electron trapping. Recent experiments were carried out by using the newly implemented "pinger" and by varying the machine transition gamma to explore further the "e-p" instability and the nature of the instability. This paper summarizes some of these recent experimental results and theoretical studies.

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 ($\sim$ 0.25 μs), which drives a neutron source. Key PSR parameters include: kinetic energy 797 MeV, circumference 90.1 m, revolution frequency $\Omega/(2\pi)$ = 2.875 MHz, betatron tunes $\nu_x, \nu_y \approx 3.17, 2.13$, and present operating intensity $N \approx 2.35 \times 10^{13}$ particles. The design intensity is 100 μA on target at 12 Hz, which implies 5.2×10^{13} protons/pulse. Average and peak intensities have been somewhat less (80 μA at 20 Hz, and 4×10^{13} maximum pulse size). The average current has been limited by slow beam losses, and individual pulse intensities are limited by a fast instability [1] and [2].

The instability appears when more than $\sim 2 \times 10^{13}$ protons are stored in bunched mode (rf on), and when more than $\sim 5 \times 10^{12}$ 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. Initially, impedance couplings were suspected to be the cause of the instability. Searches for a possible impedance source were unsuccessful, while some observations were found to support the hypothesis that the instability may be caused by the coupled oscillation between the proton beam and the trapped electrons — the "e-p" instability which has been previously observed in some other proton facilities. Supporting observations include: degrading the vacuum makes the beam become more unstable, biasing the foil to a voltage sufficient to clear electrons in the vicinity increases the stability threshold, and moving in the halo scrapers to produce more secondary electrons decreases the threshold. Supporting calculations have also shown that the conditions for "e-p" instability may occur in the PSR. While there are no clearing electrodes to remove charges, it has been generally observed that varying the conditions that may change the electron production does vary the threshold of the beam instability. However, a dominant electron source is not yet identified. The stripping foil may be a good source.

It was conjectured that electrons have to be stably trapped within the space-charge potential of the circulating beam for more than a revolution period of protons to cause the "e-p" instability. For an ideally bunched beam in the PSR with a beam-free interbunch gap of $\sim$100ns passing through the electrons every turn, trapping enough electrons for instability seems to be difficult. However, calculations and simulations based on the PSR parameter values and injection process have shown that a small amount of beam may leak into the gap to form a smooth overall density distribution and an electric potential sufficient for electron trapping [3]. Observations did show that the instability is associated with bunch leakage: with bunched beam (rf on), it has been generally observed that instability occurs when the interbunch gap has filled in. Measurements under various conditions indicate that gap filling occurs before or simultaneously with the beginning of growing oscillations. Also, experiments were performed to lower the threshold and to create the instability by deliberately injecting a small amount of beam into the interbunch gap. Other experimental evidence supporting the hypothesis of gap-filling induced instability include: the beam stabilization by kicking the leakage out of the interbunch gap during storage, and the storage of a much more stable beam by injecting proton pulses with shorter width deeper into the confining rf bucket to make leakage difficult.

Understanding of this instability and methods of controlling it have taken on new importance as the neutron scattering community considers the next generation of accelerator driven spallation neutron sources, which call for peak proton intensities of approximately 2×10^{14} per pulse or higher. Recent experimental studies of beam stability in the PSR were carried out by using the "pinger" and by varying the machine transition gamma to understand further the nature of the instability as well as the relation between the gap leakage and the instability. Theoretical study was concentrated on a simple simulation

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of the "e-p" instability. This paper reports some of the progress made in these recent studies.

II. EXPERIMENTAL OBSERVATIONS

A. Experiments Using The Pinger

These are the experiments using the newly installed "pinger", a pair of 4 m long 7.5 cm wide electrodes, to keep the gap clean and to "shake" the electrons away from the proton beam. Since the details are reported in a separate paper in this conference [4], only the results of the stability study will be summarized at here.

We adjusted the fractional part of the vertical tune near 1/6. A pulsed voltage of a few kV, ~100 ns long in time and synchronized with the gap, was then applied to the pinger once per six turns. More than 10% of increase in the instability threshold current was possible by resonantly kicking out the protons that leaked into the gap. In another experiment, we tried to shake electrons from the proton beam by applying to the pinger a continuous oscillating voltage (a few kV) of frequencies close to $n\Omega/(2\pi) \pm \nu_y$ (n integer). We also found about 10% of increase in the threshold current. These results are consistent with the "e-p" assumption and are similar to those obtained previously by using different instruments [2].

B. Low Transition Gamma Experiments [5]

The purpose of this experiment was to further study the role of gap leakage in the PSR instability. Theoretically, lowering the machine transition gamma (γ_t) in the PSR will decrease the longitudinal mobility of particles. Therefore, at lower γ_t, if the beam is allowed to debunch freely, more time is needed for particles to move into the gap. If the instability is due to the gap leakage, then after switching off the rf during storage, the time period for the beam to remain stable should be longer at lower γ_t.

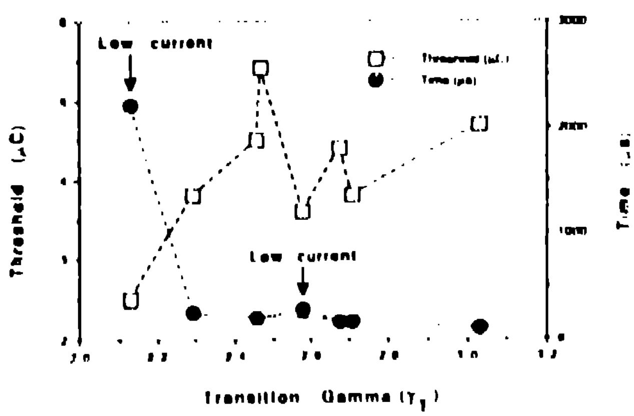

Figure 1. The γ_t dependence of the threshold charge per bunch and the stable storage time after the rf is off.

In this experiment, γ_t was varied from 2.1 to 3.1. For each γ_t, the stability threshold was first examined by varying the amount of injected charges. Then, during the storage of a marginally stable beam, the rf was turned off and the time duration between the rf off and the onset of the instability was measured.

Figure 1 summarizes the observed threshold charges and the stable storage time after the bunching rf was switched off. The results indicate that stable storage time without rf increases when γ_t is decreased. This result fits well with the theory of gap-leakage induced "e-p" instability. Since the γ_t of PSR cannot be varied without altering the tunes, high current can not be stored at all values of γ_t. The long storage times at $\gamma_t = 2.129$ and 2.578 correspond to the low currents at these points. At $\gamma_t = 2.129$ only a small amount of beam can be stored because of momentum spread is much greater than the momentum aperture (0.4 - 0.5 %). At $\gamma_t = 2.293$ and 2.578, the small working areas in the tune space limit the maximum beam currents that can be stored.

C. Frequency Spectra Observations

Previous frequency spectrum studies of the beam oscillations were based on measurements using an HP 8563B spectrum analyzer and the Fast Fourier Transforms of digitized position monitor data [2]. Recent studies have employed the autocorrelation method for the power spectra. This method enhances the signal to noise ratio in the frequency domain, and hence allows a better examination of the main peaks of the relatively broad band spectrum. Similar to the previous observations, spectra of broad bandwidths (10-50 MHz) with peaks near 100 MHz were obtained when instability occurs. The peak location can vary between 40 to 200 MHz, depending on beam conditions. These observed variations in peak location and width are consistent with the hypothesis of "e-p" instability.

III. THEORETICAL STUDIES

We consider a proton bunch with a round cross section of radius a propagating inside a perfect conducting pipe of radius b. The transverse focusing force is assumed to vary linearly with the radial distance. We also assume that in the equilibrium state, all the trapped electrons are oscillating inside of the proton beam, and particles are uniformly distributed in the transverse direction. Accordingly, the trapped electrons experience a linear transverse focusing force due to the net charge in the beam. Both the line densities of protons, λ_p, and electrons, λ_e, may vary from the head to the tail of the beam. A Cartesian coordinate system is chosen such that the z axis is on the symmetry axis of the proton beam, and the y axis is perpendicular to the plane of the ring. Neglecting all the x motions and the z motion of electrons, and adding the damping effect, the following equations can be formulated for the motions of the centeroids of protons (Y_p) and electrons (Y_e).

$$\left(\frac{\partial}{\partial t}+v\frac{\partial}{\partial z}\right)^2 Y_p + C_{dp}\frac{dY_p}{dt}+\omega_\beta^2 Y_p = \left(\frac{2g\lambda_p r_p \chi c^2}{a^2\gamma}\right)Y_e \quad , \tag{1}$$

and

$$\frac{d^2Y_e}{dt^2} + C_{de}\frac{dY_e}{dt}+\omega_e^2 Y_e = \left(\frac{2g\lambda_p r_e c^2}{a^2}\right)Y_p \quad , \tag{2}$$

where t is the time, v is the propagation speed of the protons, C_{dp} and C_{de} are the damping constants, $g = 1 - (a/b)^2$ is the geometric factor, $\gamma = (1 - v^2/c^2)^{-1/2}$, c is the speed of light, r_p and r_e are the classical radii of a proton and an electron, respectively, $\chi(z) = \lambda_e(z)/\lambda_p(z)$ is the fraction of neutralization, ω_β is given by

$$\omega_\beta^2 = \Omega^2\nu_y^2 + \frac{2\lambda_p r_p c^2}{a^2}\left[\frac{\chi}{\gamma} - \frac{1}{\gamma^3}\left(\frac{a}{b}\right)^2\right] \quad , \tag{3}$$

and $\omega_e = (c/a)\{2r_e\lambda_p[1 - \chi(a/b)^2]\}^{1/2}$, is the bouncing frequency of electrons in the proton beam. Our theoretical study of the "e-p" instability is based on the numerical solutions of Eqs. (1) and (2).

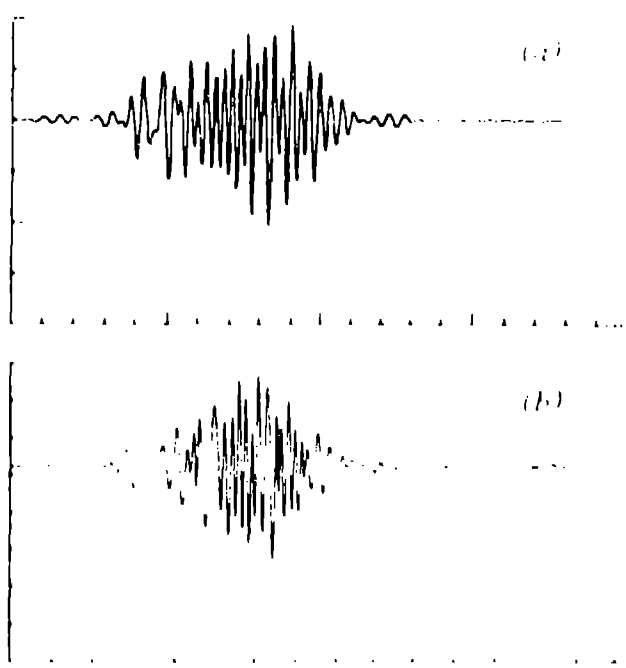

Figure 2. (a) The simulated signal of the vertical beam oscillation by using Eqs. (1) and (2). (b) The experimental data of the vertical beam oscillation.

Only one example of the numerical study will be given here. More details of the theoretical study and results will be included in another report [6]. In Figure 2, a simulated scope signal of the vertical beam oscillation, (a), is shown together with a real experimental data (b), for comparison. In this case, a cos² square pulse with a small constant density in the gap was assumed for λ_p and λ_e. The computation was initiated with resting electrons and a 100 MHz perturbation in the proton beam. One percent of neutralization was assumed. Note that in both Figs. 2a and 2b, the oscillation frequencies are correlated with the proton line density, i.e. higher at the center of the bunch and lower in the tails – more evidence that the instability is not caused by the machine impedance.

While this study is still in progress, preliminary investigations have yielded a few notable results. (1) Using the PSR parameter values and reasonably chosen values for the unknown quantities, e.g. C_{dp}, C_{de} and χ, estimated growth times are close to that observed in some experiments. (2) When we studied the effect of localized neutralization, i.e. a highly uneven electron distribution around the ring, we found the results are close to these with evenly spread electrons. (3) Gap-filling may not be a necessary condition for the "e-p" instability. The instability may still occur with a clean gap if the beam is sufficiently (a few percent) neutralized by the fresh electrons created in each turn. The instability threshold in the case of a clean gap may be somewhat higher than that in the gap filled case.

IV. SUMMARY AND CONCLUSIONS

Results from our recent experimental and theoretical studies further support the hypothesis that the observed instability in the PSR is an "e-p" instability. Recent observations are also consistent with the assumption that the instability is induced by the leakage of protons into the gap, although the theory predicts that gap leakage may not be a necessary condition for instability. A numerical tool based on a simple model has been established and is being used for instability study. Understanding of this instability and methods of controlling it have fundamental importance in both the future operation of the PSR and the design of the next generation of accelerator-driven spallation neutron sources.

One of our future main activities will be to identify dominant electron sources and to clear the electrons. In the forthcoming experiment we are planning to install clearing electrodes near the injection stripper foil where the beam losses are relatively large. We expect the theoretical studies and the experiments using pinger to continue into the near future.

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