RECENT STUDY OF BEAM STABILITY IN THE PSR*

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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 to 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 installed "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 (~1 ms) by multiturn injection through a stripper foil and compress that beam into a short single-turn extracted pulse (~0.25 μs), which drives a neutron source. Key PSR parameters include kinetic energy of 797 MeV, circumference of 90.1 m, revolution frequency of $\Omega/(2\pi) = 2.875$ MHz, betatron tunes ν_x and $\nu_y \approx 3.17$ and 2.13, respectively, and present operating intensity of $N \approx 2.35 \times 10^{13}$ 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 is limited by slow beam losses, and individual pulse intensities are limited by a fast instability [1,2].

The instability occurs when more than $\sim 2 \times 10^{13}$ protons are stored in bunched mode (rf on), and when more than $\sim 5\times10^{12}$ are stored in unbunched mode. Transverse oscillations at ~100 MHz are seen, and grow exponentially at time scales of 10–100 μs, causing beam losses. Initially, we suspected that impedance coupling was the cause of the instability. Our searches for a possible impedance source were unsuccessful, although some observations supported our hypothesis that the instability may be caused by the coupled oscillation between the proton beam and the trapped electrons – the "e–p" instability that has been previously observed in some other proton facilities. Supporting observations include the following: 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 the halo scrapers into the beam pipe 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 has not yet been identified. A possible dominant source is the stripping foil.

We 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 inter-bunch gap of ~100 ns 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 the 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), we observed that instability occurs when the inter-bunch gap has filled in. Measurements taken under various conditions indicate that gap filling occurs either before or simultaneously with the beginning of growing oscillations. In addition, experiments were performed to lower the threshold and to create the instability by deliberately injecting a small amount of beam into the inter-bunch gap. Other experimental evidence supporting the hypothesis of gap-filling-induced instability include (1) beam stabilization by kicking the leakage out of the inter-bunch gap during storage and (2) 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 $\sim 2\times10^{14}$ per pulse or higher. Recent experimental studies of beam stability in the PSR were carried out by using the newly installed "pinger", a pair of 4-m-long by 7.5-cm-wide electrodes, and by varying the machine transition gamma to understand further the

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nature of the instability as well as the relation between the gap leakage and the instability. Our theoretical study concentrated on a simple simulation 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"

We performed experiments using the pinger to keep the gap clean and to "shake" the electrons away from the proton beam. Because the details of the experimental methods are reported in a separate paper in this conference [4], only the results of the stability study will be summarized here.

We first adjusted the fractional part of the vertical to ~ 1/6. We then applied pulsed voltage of a few kV, ~100 ns long and synchronized with the gap, to the pinger once every six turns. A more than 10% increase of 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). This experiment also resulted in about a 10% increase in the instability threshold current. The results of both experiments 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 a result of 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.

In this experiment, γ_t was varied between 2.1 and 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 with rf off increases when γ_t is decreased. This result fits well with the theory of gap-leakage-induced e–p instability. Because the γ_t of the PSR cannot be varied without altering the tunes, high current cannot 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 the 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.

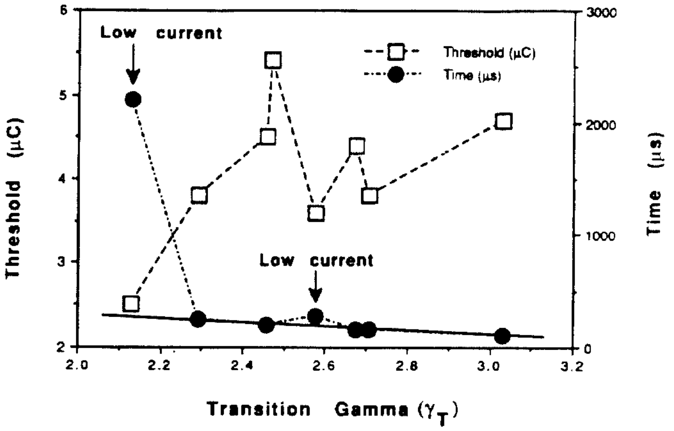

Figure 1. The γ_t dependence of the threshold charge per bunch and the stable storage time after the rf is off.

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 varies 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 STUDY

In our theoretical study, 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, we formulate the following equations for the motions of the centeroids of protons (Y_p)

and electrons (Y_e):

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

and

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

where t is the time, v is the propagation speed of the protons, $g = 1-(a/b)^2$ is the geometric factor, C_{dp} and C_{de} are the damping constants, $\gamma = (1-v^2/c^2)^{-1/2}$, 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

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

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).

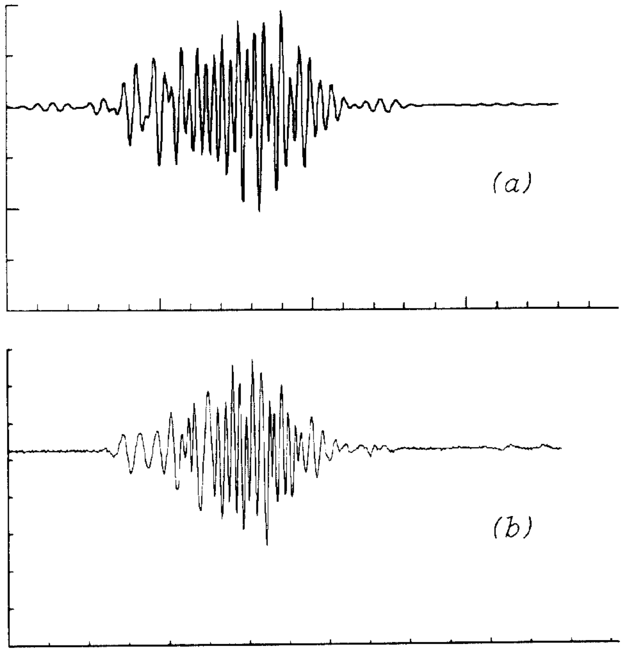

Figure 2. (a) The simulated signal of the vertical beam oscillation by using Eqs. (1) and (2); (b) The experimental data of the vertical beam oscillation.

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]. Figure 2a shows a simulated scope signal of the vertical beam oscillation, and Figure 2b shows real experimental data for comparison. In this case, a cosine 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 Figures 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. This correlation provides more evidence that the instability is not caused by the machine impedance.

Although 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, we estimated growth times that are close to those 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 those 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 the threshold 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 our theory predicts that gap leakage may not be a necessary condition for instability. We have developed numerical tool based on a simple model that we are using for further study of the instability. 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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