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ACTIVE DAMPING OF THE E-P INSTABILITY AT THE LANL PSR*

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Abstract

A prototype of an analog, transverse (vertical) feedback system for active damping of the two-stream (e-p) instability has been developed and successfully tested at the Los Alamos National Laboratory Proton Storage Ring (PSR). This system was able to improve the instability threshold by approximately 30% (as measured by the change in RF buncher voltage at instability threshold). Evidence obtained from these tests suggests that further improvement in performance is limited by beam leakage into the gap at lower RF buncher voltage and the onset of instability in the horizontal plane, which had no feedback. Here we describe the present system configuration, system optimization, results of several recent experimental tests, and results from studies of factors limiting its performance.

INTRODUCTION

A great deal of evidence indicates that the primary instability that limits the performance of the PSR is a two-stream electron-proton (e-p) instability [1,2]. This instability is manifested in coupled coherent vertical oscillations of the proton beam and the electron cloud that is present in the vacuum chamber and confined by the electric potential of the proton beam. Growth of the electron cloud results from multipacting of the electrons on the walls of the vacuum chamber during passage of the trailing edge of the proton beam, when the electrons can receive a net acceleration toward the wall. The instability is controlled by various measures to enhance Landau damping, however these measures increase beam losses in the PSR and in the transport from the PSR to the targets. Transverse feedback offers the prospect of controlling the instability without this deleterious effect.

The primary method of controlling the instability via Landau damping is increasing the voltage applied to the beam by the h=1 buncher, thus our main qualitative measure of the effectiveness mitigation techniques is the reduction of buncher voltage at the threshold of instability.

The nature of the e-p instability and of the long-bunch beam in the PSR present some challenges for a damping system: The growth rates are rapid, about 25-100μs growth time; the oscillations are broad-band, about 50-300MHz, with a central frequency that varies with the beam parameters and the conditions of the electron cloud; the driving mechanism, the electron cloud, is more variable and uncertain than driving forces for instabilities caused by structural impedances. These challenges have driven the design of the damping system.

DAMPING SYSTEM

As the instability usually occurs in the vertical plane only, this prototype system was designed for feedback in that plane only. A simplified block diagram of the system is shown in Figure 1. An existing short strip-line beam position monitor (BPM) is used as a pickup to sense coherent beam motion. The vertical difference signal (Δv) is formed with a hybrid 180° splitter and is sent through a variable attenuator to allow us to adjust the level of the signal in the rest of the system. A fiber-optic link delays the signal with high fidelity for several hundred nanoseconds, as the feedback signal is applied 4 turns (1.4μs) after the pickup in order to ensure an odd multiple of 90° betatron phase advance between the pickup and the kick. An RF switch allows rapid gating of the feedback signal. The two comb filters can be configured in a number of ways or can be bypassed. Another variable attenuator allows adjustment of the system gain without affecting the signal level in the rest of the low-level RF (LLRF) system; this allows us to avoid saturation of components when high gain is employed. Another 180° splitter provides opposite-polarity signals, via pre-amplifiers, to two 100-Watt power amplifiers and then by coaxial cable to the downstream ends of the two strip-line electrodes of the kicker.

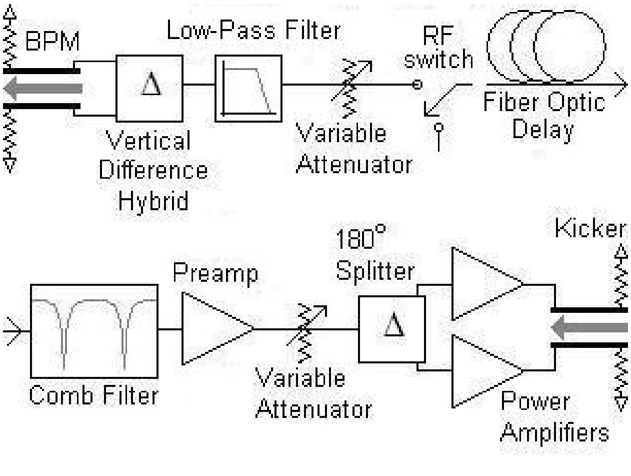

Figure 1: A block diagram of the damping system.

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System Performance

Figure 2 shows the most obvious indication that the system damps the unstable beam motion. The rapid exponential growth of the Δv signal that is present with the damping system turned off disappears when the system is turned on.

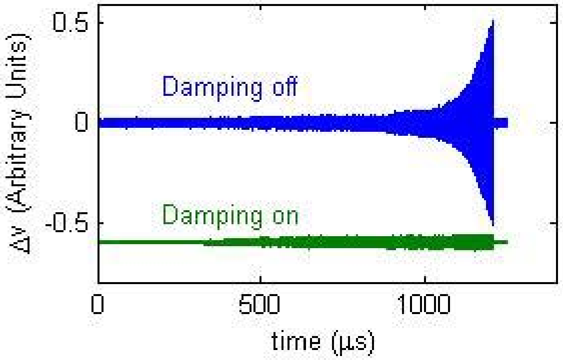

Figure 2: Vertical difference signals with and without the damping system.

Employing the damping system results in a 30% reduction in the buncher voltage required to keep the beam stable. This is similar to the improvement afforded by other mitigation techniques such as using higher-order multipole magnets to increase Landau damping. Our continued efforts have focused on experiments to elucidate the factors limiting performance of this system.

EXPERIMENTS

We've recently conducted experiments designed to explore the factors that limit the performance of the system and to test the system under conditions that are simpler than those present when the beam is unstable.

Drive-Damp Experiment

In this experiment, we drove the beam at some single frequency then rapidly turned off the drive and turned on the damping system. This rapid switching was effected through use of the RF switch shown in Figure 1; it's a double-throw switch, which allowed us to apply to the kickers either the drive signal or the feedback signal.

We hoped that this would provide us a view of the system performance under simple conditions and to observe the damping time at single frequencies. Offline analysis of the data revealed that, despite driving at a single frequency, the beam oscillated at a wide band of frequencies; this is shown in Figure 3. This motivated us to understand one of the puzzling characteristics of the e-p instability: the oscillation frequency starts in a narrow band then the frequency spread rapidly grows to a bandwidth of over 100MHz.

We have identified two mechanisms that are likely to contribute to the growth of bandwidth: 1) As the buncher causes the beam to rotate in longitudinal phase space, the projection of the oscillations onto the time axis changes, producing frequencies that are both lower and higher than those of the original oscillation. 2) Coherent space-charge tune shifts that vary along the bunch, due to the triangular pulse shape, will cause a single-frequency oscillation to become broad-band as a result of modulation of the original oscillation with a band of betatron frequencies. We have planned a set of experiments to observe and understand these two mechanisms.

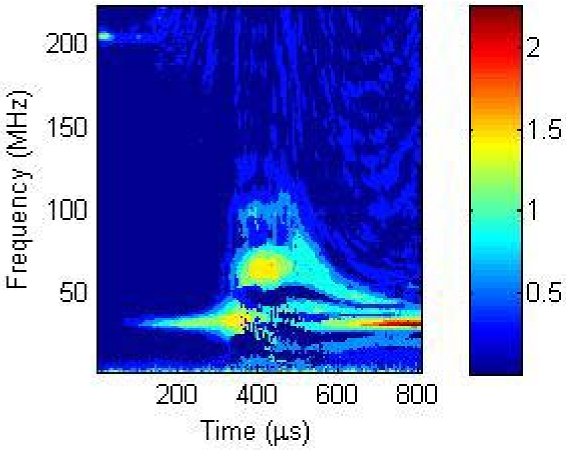

Figure 3: Fast Fourier Transform (FFT) analysis of the Δv signal with the beam driven at the upper betatron sideband of mode 10, about 28MHz. The FFT is computed turn-by-turn and the power spectral density is indicated by the colors.

Noise-Driven Beam

In this experiment, we drove the kicker of the damping system with a noise signal at the maximum power that the power amplifiers could provide. The noise was generated by cascading three solid-state amplifiers, with a terminator on the input of the first amplifier. The motivation for this test is the notion that the noise may interfere with the phase information carried in the head of the beam, thereby enhancing stability [3]. While this experiment isn't a direct test of the damping system, it is a test of the possibility that the enhanced stability afforded by the damping system is due entirely to this mechanism.

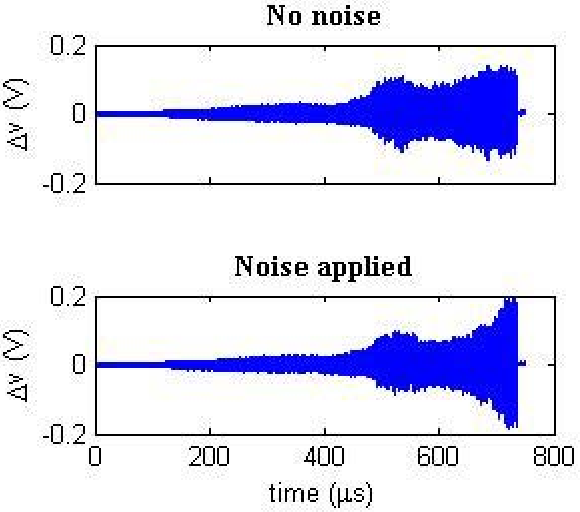

Figure 4: The effect of driving the beam with a noise signal.

The noise made the beam slightly less stable; while no instability threshold curve was measured, we observed growth in the Δv signal that is typical of the onset of instability, as shown in Figure 4

Signal Saturation Study

The system has been configured to avoid signal compression (saturation) as long as the input Δv signal power remains below -14dBm; the input signal is monitored to ensure this condition. As a consequence, the feedback is small early in the instability before the Δv signal becomes large. We tested the system with the input attenuator turned down, resulting in a larger input signal early in the instability and signal compression later. The system performs better under that condition.

Two factors may contribute to this enhance performance: 1) Applying feedback with high gain early in the instability may prevent the conditions that lead to instability later in the cycle. 2) Operating in saturation may not have the significant deleterious effects, such as system phase shifts and bandwidth reduction, that we suspected it might have. We have planned experiments and system measurements that will allow us to better understand this aspect of the system.

Longitudinal Noise

The orbital frequency of the PSR beam is normally an integer subharmonic of the frequency of the linac accelerating field, specifically 201.25MHz÷72.00. This frequency was chosen because it's fairly easy to produce a stable reference using logic circuits to divide the linac reference signal. This integer subharmonic however has the undesirable effect of stacking the linac micropulses atop one another in the PSR, creating intense space charge forces at the micropulse locations. Additionally, this creates broad-band longitudinal structure on the circulating beam; this structure results in noise in the damping system because the Δv signal is proportional to the instantaneous beam current.

As an experimental test during the 2006 run cycle, we used a non-integer subharmonic PSR reference frequency in order to interleave the linac micropulses. During machine development periods this modified frequency resulted in less longitudinal structure, a less intense electron cloud and improved stability. Figure 5 shows Δv signals and beam positions with the integer and non-integer subharmonic frequencies. The noise in the Δv signal is dramatically reduced with the non-integer subharmonic; we expected that this reduction of noise would lead to improved performance of the damping system.

We found no improvement in the performance of the damper system resulting from use of the non-integer subharmonic. The damping system yielded a 30% reduction in buncher voltage at the threshold for instability, just as in the case of using the integer subharmonic. We plan to pursue this issue further in order to understand the role of noise in limiting the performance of the damping system.

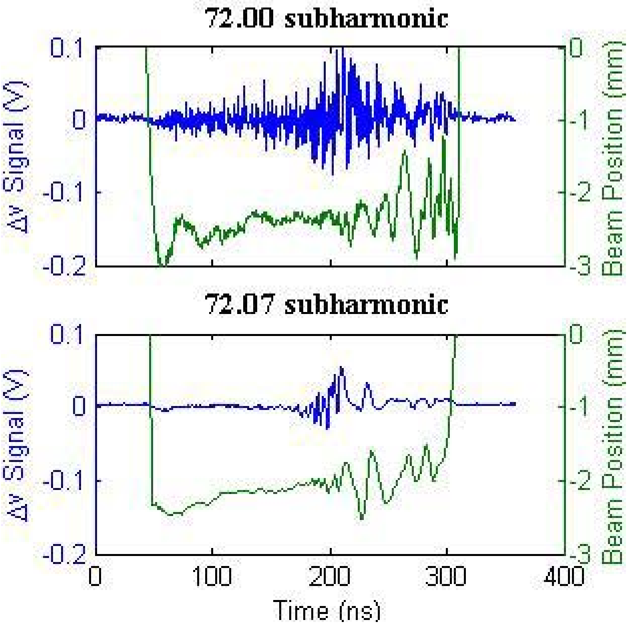

Figure 5: Beam position (green) and Δv signals (blue) with the PSR orbital frequency set to the 72.00 and 72.07 subharmonics of the linac. The data are from one passage of the beam through the BPM, and the beam position is the integral of the difference signal divided by the integral of the sum signal.

FURTHER STUDIES

We plan to run several experiments in 2007 with coasting beam, i.e. with the buncher off, with small beam current. This will create conditions that are simpler than those present when the instability occurs. The drive-damp experiments mentioned above should prove to be more illuminating in this mode. Also, further studies of the effects of the non-integer subharmonic revolution frequency, particularly the noise reduction, are planned.

SUMMARY

We've shown the results of some tests of the transverse damping system at the LANL PSR designed to help us understand the limitations of performance of the system and to test the system under simple conditions. Plans for several further experiments have been stimulated by these tests. Additionally we've gained some insight behind the mechanisms leading to the growth in the frequency spread of the beam oscillations that we typically see associated with the instability.

REFERENCES

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[3] P.Channell, private communication.