EXPERIMENTAL TESTS OF A PROTOTYPE SYSTEM FOR ACTIVE DAMPING OF THE E-P INSTABILITY IN THE ORNL SNS ACCUMULATOR RING*

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Abstract

The prototype of an analog transverse (vertical and horizontal) feedback system to actively damp the electron-proton (e-p) instability has been developed and tested on the ORNL Spallation Neutron Source (SNS). The principle components, system configuration, and a review of several experimental studies geared towards understanding the current performance and limitations of the system are described.

INTRODUCTION

The Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL) is currently a 925 MeV accelerator with an accumulator ring used to provide 1 MW of beam to the spallation target. Typical beam parameters consist of approximately 18 uC pulses, ~695 nanoseconds wide at a 60 Hz pulse repetition frequency.

As SNS continues to increase the beam intensity and power, the onset of the e-p instability may increase beam losses thereby limiting the amount of power deliverable to the target. A similar analog system developed at the proton storage ring (PSR) at Los Alamos National Laboratory (LANL) [1-2] showed a significant increase in the e-p instability threshold, but was limited to a single transverse plane (vertical). Recent studies and simulations of the SNS accumulator ring have shown that the e-p instability is wideband [3], and therefore needs a feedback system with a wide enough bandwidth to stabilize the beam in the ring. The current system under development at SNS has two independent feedback systems, one for each transverse plane (vertical and horizontal).

ANALOG SYSTEM DESCRIPTION

A simplified block diagram of the currently deployed analog feedback system, for one transverse plane, is shown in Figure 1. Descriptions of each component follow.

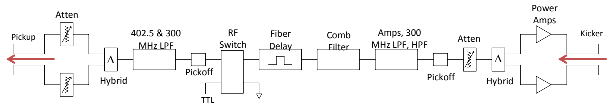

Figure 1: Schematic of the wideband feedback system.

The signals in Figure 1 flow from left to right. The pickup and kicker electrodes are new stripline electrodes, 50 centimeters in length, specifically designed for the feedback damper system. The individual electrode signals from the pickup electrodes are passed through variable attenuators to minimize the stable beam electrical axis of the pickup electrodes. The individual electrode signals then pass through a 180 degree hybrid, producing a difference signal that is proportional to the beam intensity and position.

Observations of the signal spectrum showed that 402.5 MHz from the LINAC is carried by the beam into the accumulator ring, so a 402.5 MHz stub filter was designed and built to attenuate this and higher frequencies up to 1 GHz. The signal is then filtered using a 300 MHz filter with a flat time delay (Mini-Circuits SBLP-300) to limit the bandwidth for the high power amplifiers to be discussed later.

The next component is a high impedance pickoff, which is used to observe the difference signals during operations [2]. Following the pickoff, a TTL RF switch (Mini-Circuits ZYSWA-2-50DR) is used to turn the LLRF system on or off at various times during beam accumulation or storage. For the experiments thus far, the switch has only been used to turn on the feedback signal at the beginning of accumulation and turn off after the beam extraction from the ring.

Following the switch is a fiber-optic based delay line system. Considering the current operational tunes for SNS and the location of the pickup and kicker electrodes in the accumulator ring, a delay of one turn has been determined to be optimal for damping at a 90 degree phase advance. SNS has a ring period of approximately 957.5 nanoseconds, so accounting for the delay from the pickup electrodes to the LLRF, and the LLRF to the kicker electrodes, a total delay through the LLRF needs to be approximately 400 nanoseconds. Using fiber-optics with an operator-switchboard style "plug-and-play" box provides the ability to quickly adjust the delays for different ring configurations, with total delays of up to 10 microseconds and resolutions of 50 picoseconds.

Following the delay lines, a comb filter system, using the same fiber-optic based technology (MITEQ SCML-50K6G) as the delay lines, is used to resonate out the ring frequency harmonics. The comb filters for each axis were designed to have two individual single turn filters as well as two individual two turn filters available for use. Having two of each turn filter allows for testing several different machine configurations as well as the ability to cascade the filters if desired.

Following the comb filter is a series of two low noise amplifiers, three high pass filters, and another 300 MHz filter (Mini-Circuits SLP-300). Due to the low noise

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amplifiers producing oscillations in the 60 kHz range, high pass filters were built with corner frequencies of approximately 1 MHz to remove the oscillations. The 300 MHz filter is just to limit the signal bandwidth one last time prior to reaching the power amplifiers.

Another high impedance pickoff is used to monitor the signals before passing through a set of variable attenuators and exiting the LLRF, used to adjust the overall LLRF system gain. After the attenuators the signal is sent through a 180 degree hybrid and then on to the high power amplifier controllers. The controllers split the incoming signal for parallel amplification in each of the individual high power amplifiers [4].

The vertical system produces 200 W in each channel while the horizontal system produces 400 W in each channel. High impedance pickoffs have also been installed following the power combiners to monitor the output signals.

SYSTEM PERFORMANCE RESULTS, ISSUES, AND CONCLUSIONS

A set of sample measurements illustrating the performance of the analog feedback system follow. Figures 2 and 3 depict the spectra of the signals from the first high impedance pickoffs in the vertical and horizontal LLRF systems. In both figures the mode axis is the frequency of oscillations normalized to the ring frequency, the turn axis represents the turns of the beam around the ring, and the vertical axis is the log of the magnitude squared of the Fourier transformed time domain signals.

The vertical system (Fig. 2) shows a significant amount of e-p reduction in the last 200 turns out to about the 100th mode (~ 100 MHz). The horizontal system (Fig. 3) shows a slight amount of e-p reduction in the same frequency region, the effect is not as significant as the vertical.

During the experimental tests of the feedback damper system, several issues have been shown to limit the systems effectiveness. The following is a brief discussion of these issues.

Although we have demonstrated the ability to damp the e-p instability there seems to be a large discrepancy between the damping ability in one transverse plane relative to the other. Typically the vertical system has shown better damping than the horizontal, which could be due to the slightly different damping rates because of the different beta function values in each transverse plane at the pickup and kicker electrodes. This issue could be offset by upgrading the total output power of the damper system.

Another issue appears to be the shot-to-shot variation of the beam in terms of growth rates of the e-p instability. While observing the feedback damper system operating, there would be several shots where the system appeared to be working, but on subsequent shots it would appear to not be working. By inserting the comb filters the shot-to-shot variation in the difference signal is significantly reduced.

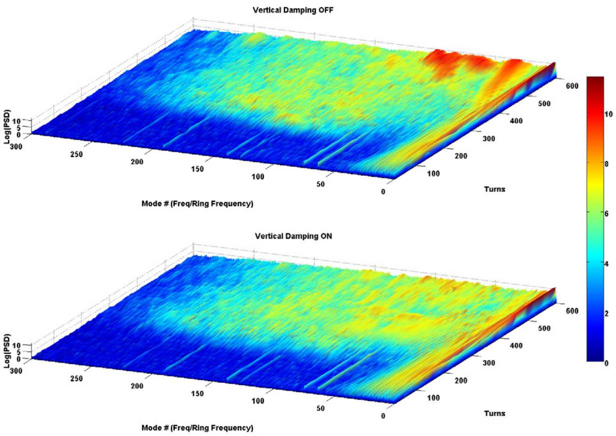

Figure 2: Vertical spectrum with the feedback system off (top) and the damping feedback system on (bottom).

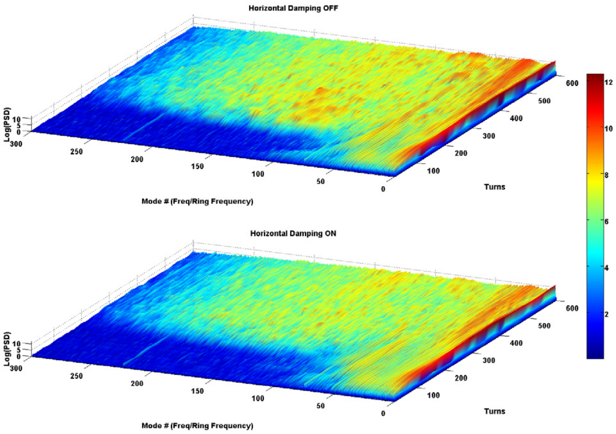

Figure 3: Horizontal spectrum with the feedback system off (top) and the damping feedback system on (bottom).

One final issue currently seems to be the apparent limited bandwidth of the damper system in both the vertical and horizontal systems. As a test of the individual systems, the outputs of the LLRF were reversed so as to drive the beam in a positive feedback manner. The frequency spectra for the vertical and horizontal systems are shown in Figure 4. This shows that both systems appear to only have the ability to affect the beam out to the 100th mode (~100 MHz). This corresponds to the same frequency range that was observed to damp in the individual systems (Figs. 2-3).

To investigate the possible causes for the limited bandwidth of the damper system, a series of Beam Transfer Function (BTF) measurements were made. The BTF measurements were obtained by placing a network analyzer (NWA) in-line between the pickoff and RF switch in the LLRF (see Fig. 1). This location is advantageous because the RF switch gating helps protect the high power amplifiers.

Maximizing the Intermediate Frequency Bandwidth (IFBW) on the NWA minimizes the time required for data acquisition. The NWA was set to its highest IFBW of 6 kHz which corresponds to ~300 microseconds of acquisition time, thus for SNS about 300 turns in the accumulator ring. For the measurements that follow, the trigger timing was set so that the NWA was examining turns 100 to 400 during accumulation.

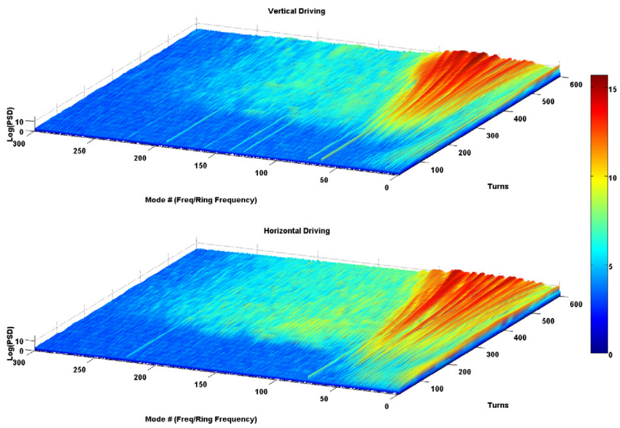

Figure 4: Vertical (top) and Horizontal (bottom) spectrum by driving the beam unstable.

Figure 5 shows the magnitudes of the BTF for the horizontal (top) and vertical (bottom) planes. The horizontal axis of Figure 5 is the tune, the vertical axis is the mode (harmonic number x ring frequency), and the colorbar is the magnitude of transmission in dB. The upper side bands (USB) clearly show the individual tunes for each transverse plane, with a horizontal tune of ~ 0.225 and a vertical tune of ~0.168. Of note is the fact that the USB rolls off significantly at about the 90th mode (~90 MHz), corresponding to about the same bandwidth of damping and driving (see Figs. 2-4).

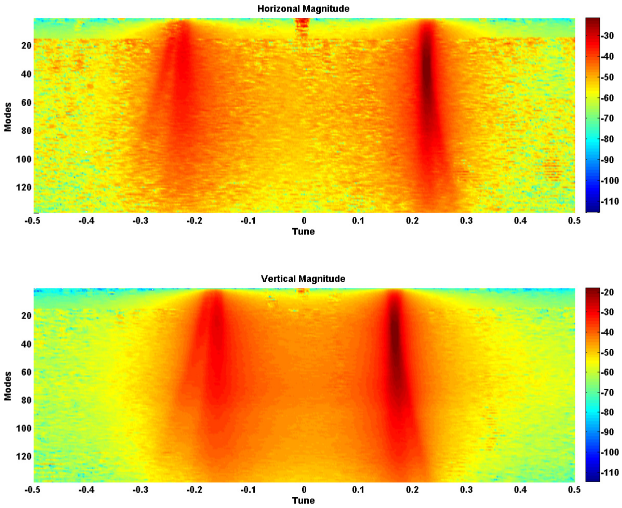

Figure 5: Horizontal (top) and Vertical (bottom) Beam Transfer Function spectra.

Examining the NWA data further, line-outs of the magnitude and phase along each respective USB tune are shown in Figure 6. The vertical axis of the upper plot in Figure 6 is the magnitude of transmission in dB and the horizontal axis is the frequency mode. Both the horizontal (red) and vertical (black) transmission characteristics are nearly identical in terms of their peak modes as well as their decay rate as a function of frequency.

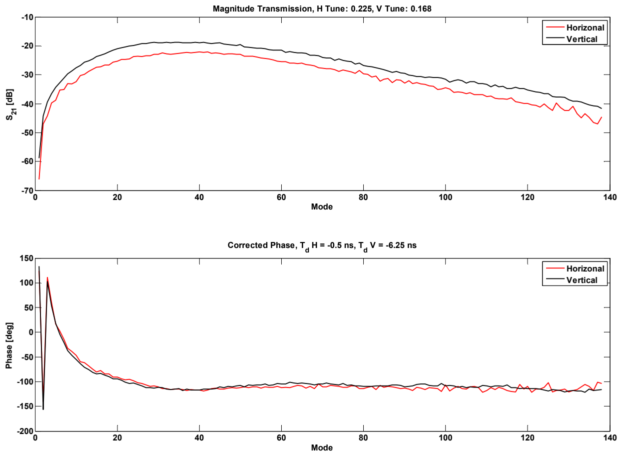

Figure 6: Magnitude Transmission (top) and Phase, corrected for electrical delay (bottom), of the Horizontal (red) and Vertical (black) systems at the USB.

The vertical axis of the bottom plot in Figure 6 is the phase in degrees, corrected for electrical delay, and the horizontal axis is the frequency mode. The phases for both the horizontal and vertical systems are essentially identical and flat above the 20th mode. The phases below the 20th mode are due to high pass filters in the LLRF systems.

Studies are currently being conducted to examine the effects limiting the damper system bandwidth including the kicker electrode response, Landau damping, and longitudinal beam shape.

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[4] The high power amplifiers were designed and built by InterTronic Solutions/Eltac Ltd.