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TRANSVERSE DAMPER USING DIODES FOR SLIP STACKING IN THE FERMILAB RECYCLER*

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Abstract

During slip stacking in the Recycler, up to six batches of 84 bunches each are slipped by each other to and then captured to double the intensity of the extracted beam. For nominal chromaticity settings, a bunch by bunch transverse damper system is needed to maintain beam stability but this system is blind to the bunches as they are slipping. The initial solution was to drastically raise the chromaticity to keep the beam stable. A new frequency based damper using diode detectors was developed to provide damping during slip stacking and allow the chromaticity to be reduced to nominal settings.

INTRODUCTION

Slip stacking refers to the process in which batches (84 bunches) of beam are injected and captured with slightly different RF systems so that they have slightly different energies and travel on separate orbits allowing them to slip by one another. The process was first implemented in the Main Injector to increase proton beam power for the MINOS neutrino experiment at Fermilab [1]. As part of the NOνA neutrino upgrade the Recycler anti-proton storage ring which shares the same tunnel with the Main Injector was re-purposed as a proton stacker [2]. In this configuration, slip stacking is done in the Recycler while the Main Injector is ramping which allows the overall cycle time to be reduced, further increasing the beam power.

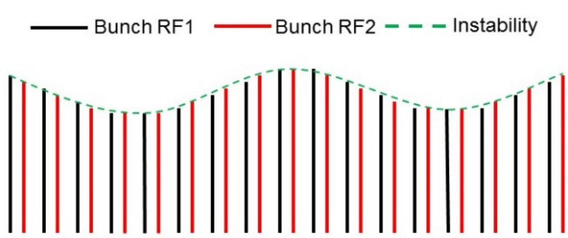

Figure 1: Cartoon showing slip stacking bunches with coupled bunch instability superimposed.

Initially the Recycler had a bunch by bunch digital damper very similar to the one used in the Main Injector [3]. These bunch by bunch systems were blind during the slipping process and needed to be disabled. This drastically increased chromaticity and subsequently tunes to provide beam stability while the dampers were off. As the Recycler struggled to reach design intensity, the high losses during the slipping forced the development of a system capable of damping the beam during the slip stacking.

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As shown in Figure 1, the damper is required to suppress the coupled bunch instabilities which are dominant at low frequencies. The first mode is at about 50KHz and the expected bandwidth is a few MHz. Because the two beams are effectively coupled, we just need to detect the envelope of the instability frequency.

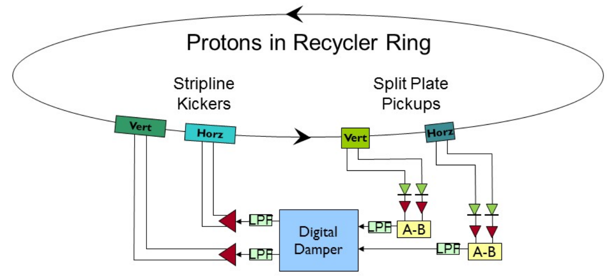

Figure 2: Overview of the current Diode Damper system in the Recycler.

SYSTEM OVERVIEW

The slip stack damper was implemented using existing components from the original Recycler anti-proton damper [4]. An overview of the system is shown in Figure 2. The system consists of a BPM pickup, input filters, digital signal processing, output amplifiers, and stripline kickers. To damp the slip stacked beam, a technique to detect the relatively low frequency coupled bunch beam instability was developed.

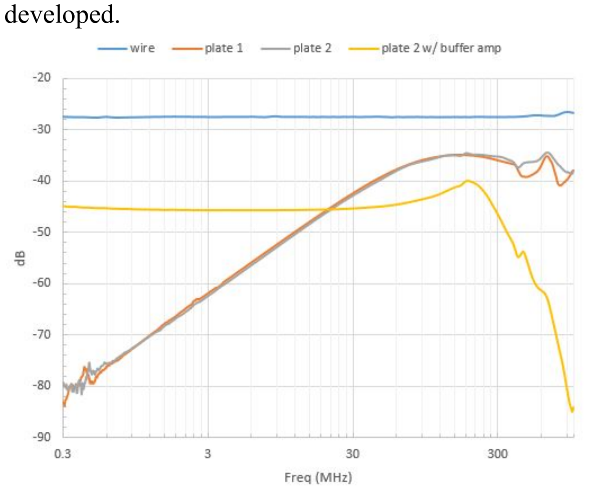

Figure 3: Measured frequency response for the split tube beam position monitor using a frequency matched wire.

The Pickup Response

The damper system uses the same split plate pickups installed in the Recycler . To measure anti-proton beam, high impedance pre-amps were installed in the tunnel to extend the frequency response of the pickup down to about 100KHz. The frequency response of the pickups is shown

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in Figure 3 and with the addition pre-amps is shown in Figure 4. For high intensity operation with short 53MHz bunches it is not feasible to use this technique. Another method is needed to extend the pickup response down to 50KHz which is needed to damp the lowest coupled bunch instability.

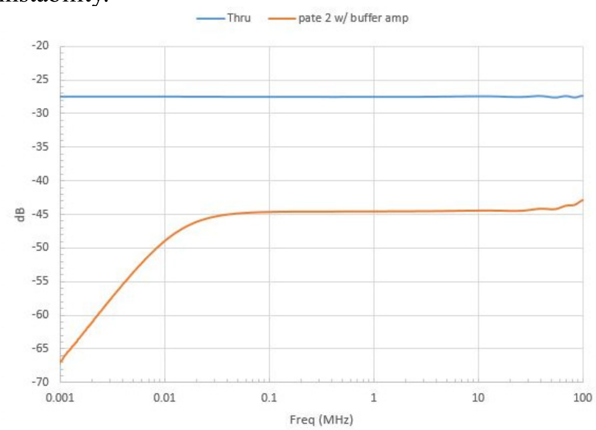

Figure 4: The frequency response of the pickup plus a high impedance buffer amplifier.

Diode Detection Technique

Several techniques were considered, but the simplest implementation was to use diodes in a configuration very similar to that used in the direct diode detection technique [5]. Fast schottky diodes were chosen which were able to detect the low frequency amplitude modulation from the beam instability riding on top of the slipping 53MHz bunches. Note, there is some secondary modulation effects due to the amplitude of the bunches increasing as they walk past one another but to first order, this is cancelled with a difference amplifier.

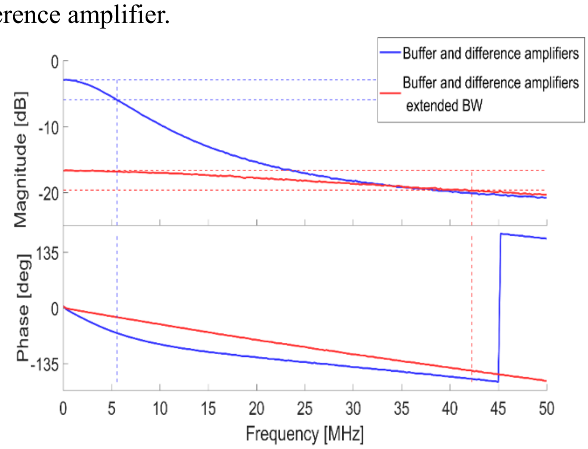

Figure 5: The frequency response of the schottky diode, buffer amplifier, and difference amplifier for the initial configuration and modified configuration.

Results of bench tests for the input circuit are shown in Figure 5. The initial configuration shown in blue had about 5 MHz of bandwidth which was thought to be sufficient. As noted in the figure, it also had non-linear phase shift over this range which could not be completely compensated for by our digital delay. The buffer amplifier was modified to extend the bandwidth and improve the system performance as the linear phase response allowed for better timing and hence damping at lower frequencies (red trace in Figure 5). The gain was reduced, but we had over 20dB of attenuation in the system which was removed to compensate for this attenuation.

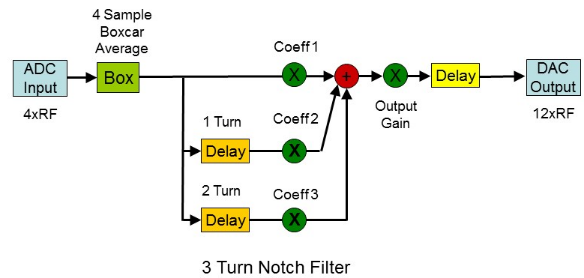

Figure 6: Block diagram for the damper firmware which consists of settable coefficients, gain, and delay.

Digital Signal Processing

The current system differs from the original anti-proton damper in that we now have one pickup instead of two. This required modifying the design to incorporate a three turn filter to notch the revolution harmonics and adjust the pickup to the kicker phase advance. A simplified block diagram of the digital filter is shown in Figure 6. For this system four bit coefficients are used which allow roughly 8° steps for the pickup to kicker phase. All relevant parameters can be controlled by the user.

COMMISSIONING

The first step in commissioning is to verify the timing and gain settings. This requires dedicated study time with low intensity beam so that open loop response measurements can be made. The results for the vertical and horizontal systems are shown in Figure 7 and Figure 8 respectively. As the tunes are near half integer, the plots are shown centered on 0.5 tune. The upper sideband is on the left and the lower sideband is on the right. The phase is inverted so that ideal damping occurs when the phase is zero at the peak.

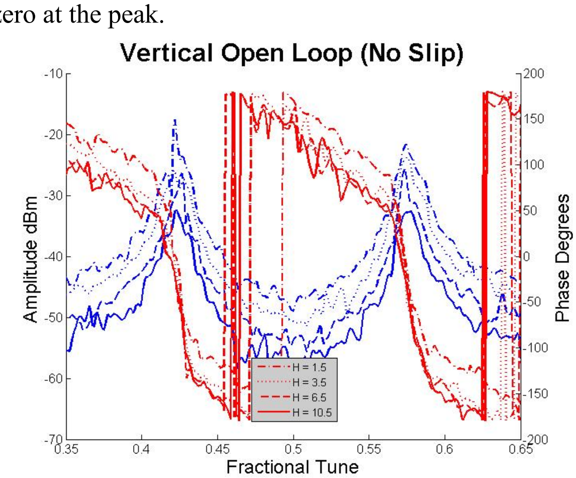

Figure 7: Vertical open loop system response. Upper sideband for n+q on the right and the lower sideband for n+1-q is on the left.

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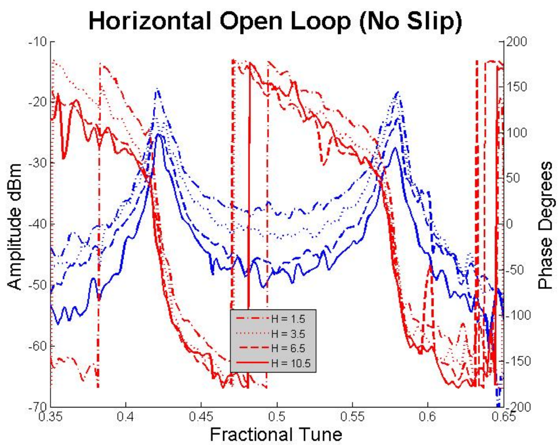

Figure 8: Horizontal open loop system response. Upper sideband for n+q on the right and the lower sideband for n+1-q is on the left.

Once the system is timed-in, the loop can be closed. Note, since one observes two tune peaks for the split tunes all open loop measurements are done with non-slipped beam. This is done to make certain the system is actually working. The sign can be flipped to anti-damp for a short time. Figure 9 shows the vertical position (blue), horizontal position (purple) traces, beam intensity (green), and the damping gate (yellow) at the end of the cycle on fully slipped beam. In this case, there is significant damping due to chromaticity, but the damper is able to overcome this and cause slow growth.

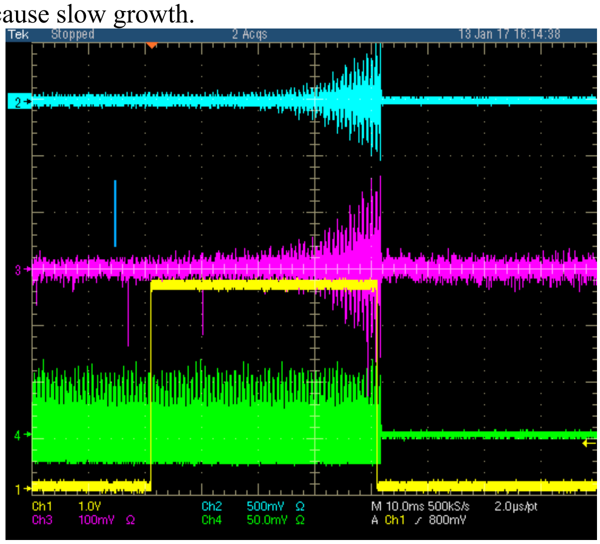

Figure 9: Ant-damped slipped beam. Blue – vertical, Purple – horizontal, Green – beam from WCM, Yellow – damping gate.

Once the damper was made operational, the Recycler experts began tuning the machine to lower the chromaticity and tune on other machine parameters. Within a matter of days of the system becoming operational, the Recycler began achieving record intensities and soon after the complex was regularly operating at or above the design 700kW beam intensity. It is also possible to use the damper system to make closed loop measurements even at full intensity as shown in Figure 10. It is possible to see the split tunes during slip stacking caused by the two different momentum beams.

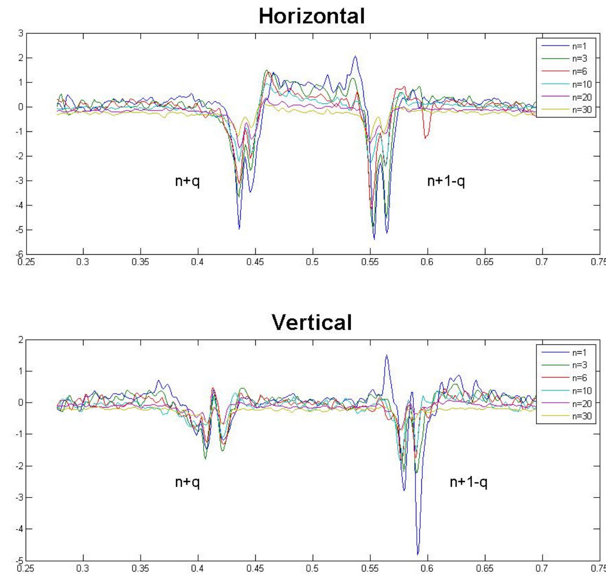

Figure 10: Closed loop response at full intensity during slip stacking.

SUMMARY

A diode detector envelope front-end was developed to allow detection of the low frequency coupled bunch instability on slip stacking beam in the Recycler. Once implemented the system allowed much easier tuning of the machine, lower losses, and achievement of design intensity operation.

ACKNOWLEDGMENT

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