A LONGITUDINAL DIGITAL MODE DAMPER SYSTEM FOR THE FERMILAB BOOSTER*

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Abstract

The Fermilab Booster accelerates bunches and accelerates proton beams from 400 MeV to 8 GeV. During the acceleration the Radio Frequency (RF) cavities are swept from 38MHz to 52.8MHz and requires crossing through transition where accelerating phase is shifted 90 degrees. In order to keep the beam stable and minimize losses and emittance growth a longitudinal damping system is required. This has traditionally been done by dedicated analog electronics designed to operate on specific beam modes for frequencies of instabilities. A complete digital implementation has been developed for this same purpose. The new digital system features and performance are detailed.

INTRODUCTION

The longitudinal damper is required to suppress coupled bunch instabilities in the Fermilab Booster and is a critical component of the high intensity machine operation [1]. The damper operates by detecting an oscillation feeding it back on the beam with the appropriate phase to create negative feedback. For a longitudinal instability these show up as synchrotron tune lines about the revolution harmonics. As the Booster is an h=84 machine, the instabilities can appear in any of the 84 revolution harmonics often referred to as modes. The approach taken in the Booster has been to build dedicated electronics to suppress each mode which has caused problems. The new digital system can be configured to provide diagnostics and damping on any of the 84 modes via software control.

DAMPER SYSTEM

An overview of the Booster longitudinal damper system is shown in Fig. 1. In the Booster the pickup is a Resistive Wall Current Monitor. In principle, the digital system can operate on any of the 84 modes, but damping requires appropriate hardware, typically a cavity, to apply the correction signal. There are currently two options in the Booster. The accelerating RF cavities are used for damping mode 1 and 2. A dedicated cavity with a center frequency of 80MHz and bandwidth of 10MHz. This is able to damp modes 42-54. A second dedicated cavity at 65 MHz is also installed but is not currently used as no destructive modes have been observed in this frequency range.

Digital Damper Hardware

A custom VME/VXS board is the heart of the damper system. It was developed for generic feedback applications and is shown in Fig. 2. It consists of 4

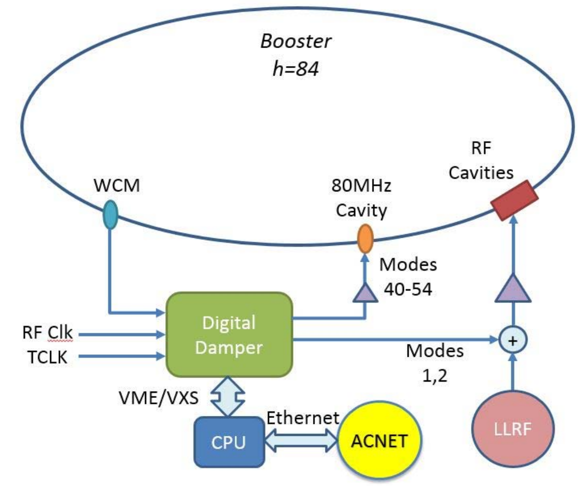

Figure 1: Overview of the Booster longitudinal damper system.

channels of 25o MS/s 14 bit ADCs and 4 channels of 500 MS/s 16 bit DACs which are connected to an Altera Cyclone V FPGA. Timing for the board is handled through a lower jitter PLL based clock distribution chip so that ADC, DAC, and logic can be synchronized with an external reference clock.

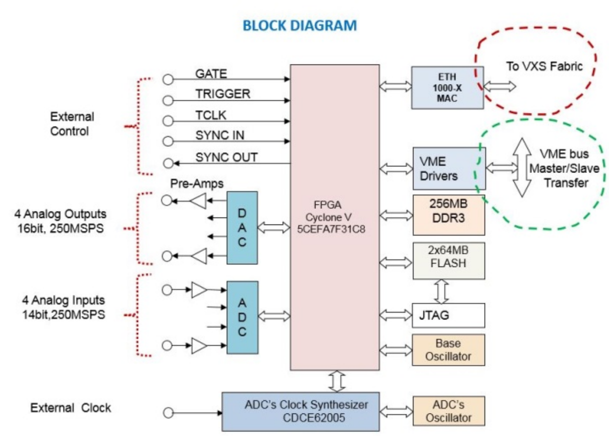

Figure 2: Block diagram for custom VME/VXS digital feedback board developed at Fermilab.

Digital Damper Firmware

A single damper board has 16 down converter channels as shown in Fig. 3. In principle, each channel can be programmed to provide either a drive or correction signal on any mode with some limitations due to hardware and system configuration. There are 4 DACs on the board and each channel can only be assigned to 1 DAC to insure

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timing integrity. In the nominal configuration, 13 channels are assigned to DAC1 to provide a programmable drive and up to 12 mode correction signals

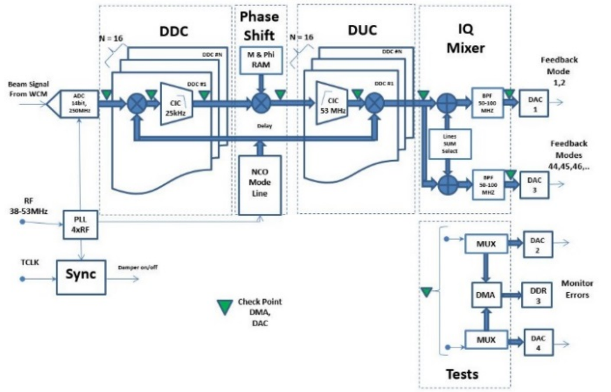

Figure 3: Block diagram of for the 16 channel narrowband damper system.

to the 80Mhz damping cavity. The final three channels provide a drive and mode 1 and mode 2 correction signals to DAC3 for feedback to the accelerating cavities. In this implementation, DAC2 & DAC4 are available for diagnostics.

The details of the narrowband channel logic are shown in Fig. 4. The basic scheme uses a quadrature down conversion followed by a CIC filter to down sample to an intermediate frequency (IF) of 25 KHz. A FIR filter is available but as the signals have been relatively clean is only used to suppress the DC component from the revolution lines. The in-phase and quadrature components are rotated to phase shift the signal. The phase shift is the key to providing negative feedback. The components can also be scaled at this stage to apply gain. The signals are then interpolated back to full rate with another CIC filter and then mixed back up to the appropriate mode frequency and summed to preserve the original sideband structure. The mixing sine and cosine terms are generated by NCOs locked to the external RF reference so they remain locked on the revolution harmonic of interest even as the machine frequency sweeps.

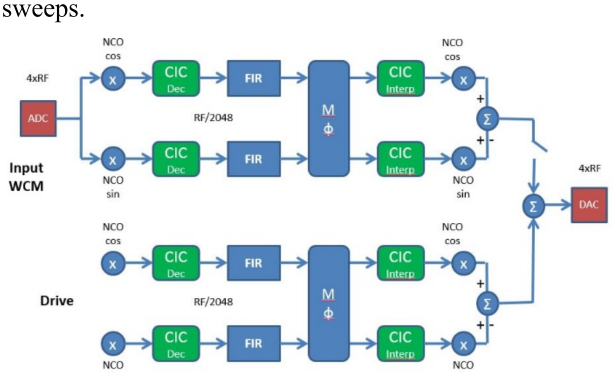

Figure 4: Block diagram for the a single mode narrowband digital down converter channel. Also shown with programmable drive channel we can be used to measure beam response.

Control Software

An ACNET application was developed which provides the ability to control and monitor the damper operation. The top level panel shown in Fig. 5 allows the operator to assign each channel to a Booster mode and determine which Booster TCLK events that mode will provide

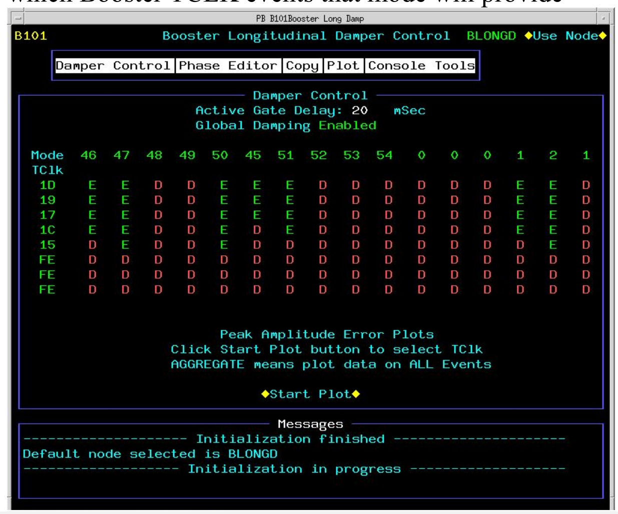

Figure 5: Main control page for the Booster longitudinal damper system.

damping on. Note, a mode can be assigned to channel but not damp to provide real time diagnostics on that mode. The application also provides the ability to set/adjust the gain and phasing for each assigned mode as shown in Fig. 6. The phase control provides the ability to copy the curve from another channel and shift the curve by +/- x degrees. To achieve damping, the correction signal must be applied to the beam at the correct phase. This is complicated in the Booster due to the frequency sweep of the RF and changing synchrotron tune. To account for this, the phase of the correction signal must be changed as a function of time. The system provides a programmable phase shift as a function of turns for each mode.

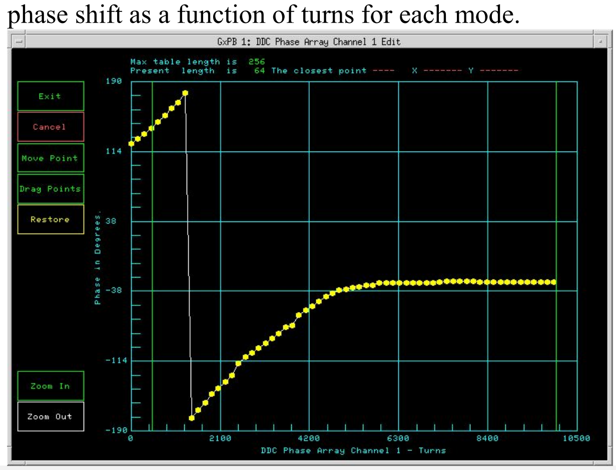

Figure 6: Graphical editor for phasing each mode. Allows user to set the phase shift as a function of turn.

On each Booster TCLK event, the mode error signal waveforms sampled at 25 KHz are readout in the front-end. From this data, the applications also provides diagnostic displays for mode power and mode error waveforms shown in Fig. 7. The displays can be configured to select which modes are displayed on and what TCLK events the displays are updated. This allows real-time monitoring of the system performance by the operators and machine experts.

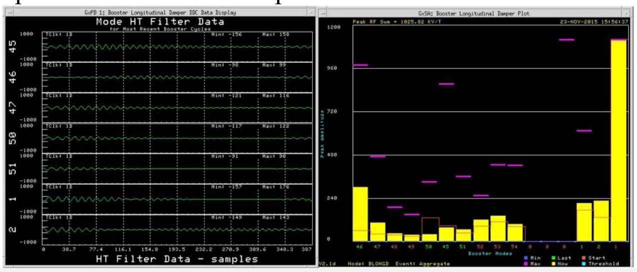

Figure 7: Damper diagnostics displays for mode error waveforms and mode peak amplitudes.

OPERATIONAL RESULTS

The system has been in operation for the past year. During most of this time, it was working in tandem with the existing analog dampers with the correction signals being summed from each system. For the last 2 months of running, the analog dampers from modes 46-52 were turned off and the machine operated successfully with just the new Digital Damper system alone. During the 2016 shutdown, the tunnel pickup (WCM) and kicker (80MHz cavity) needed to be relocated in the Booster. After the shutdown, the analog dampers will be decommissioned and just the Digital Dampers will be brought back online. The exception is the analog mode 1 damper which is the most critical damper system. Until further testing is complete, both dampers will continue to operate in tandem.

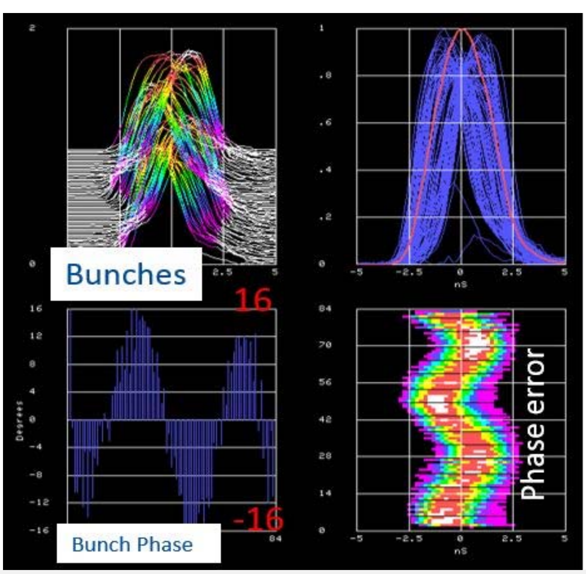

Figure 8: Mode 2 oscillation observed on beam extracted from Booster.

As the intensity in the Booster increased, a mode 2 instability was observed on the extracted Booster Beam as shown in Fig. 8. While this was not causing beam loss in the Booster, mode 2 was effecting beam emittance and performance in the downstream machines. With the digital system, it was relatively straightforward to produce a correction signal for this mode and feed it back along with the mode 1 signal to the fundamental accelerating cavities. The result after turning on the mode 2 damper is shown in Fig. 9.

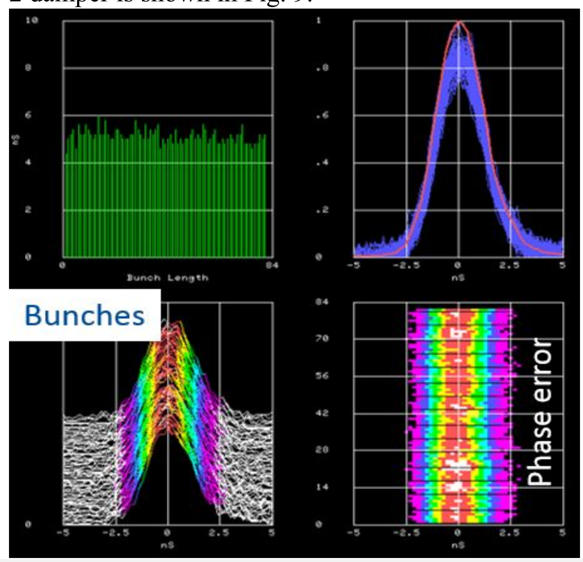

Figure 9: Extracted Booster beam after implementing mode 2 feedback in Digital Damper System the mode 2 oscillation is gone.

SUMMARY

A new Digital Longitudinal Damper system has been installed and commissioned in the Fermilab Booster. This system allows great flexibility and improved diagnostics over the previous system which had dedicated analog electronics for each mode. This is expected to be extremely useful as we continue to push the Booster to higher and higher intensities.

REFERENCES

[1] Steimel, J., and McGinnis, D. P., "Damping in the Fermilab Booster," in *Proceedings of the 1993 Particle Accelerator Conference*, IEEE, Piscataway, NJ, 1993, pp. 2100-2012.