Damping in the Fermilab Booster

James M. Steimel Jr. & Dave McGinnis
Fermi National Accelerator Laboratory*
P.O. Box 500, Batavia, IL 60510 USA

Abstract

A working prototype of a narrow band, longitudinal phase damper has been developed and tested on the Fermilab Booster. This paper will discuss the design and results of the damper as well as problems associated with designing dampers for fast frequency sweeping accelerators. Results for wide band, longitudinal dampers and transverse dampers will also be discussed.

I. INTRODUCTION

The upgrade of the Fermilab Linac from 200MeV to 400MeV will reduce the losses in the Booster due to space charge effects, but the increased beam current will cause greater coupled bunch mode instabilities. Strong coupled bunch modes exist even at present beam current levels. To suppress the coupled bunch modes, bunched beam dampers were designed.

A generic damper configuration is shown in Figure 1. The damper reduces beam oscillations via negative feedback. This paper discusses the different types of damper systems designed and tested on the Fermilab Booster. These include: narrow band and wideband longitudinal dampers, and wideband transverse dampers.

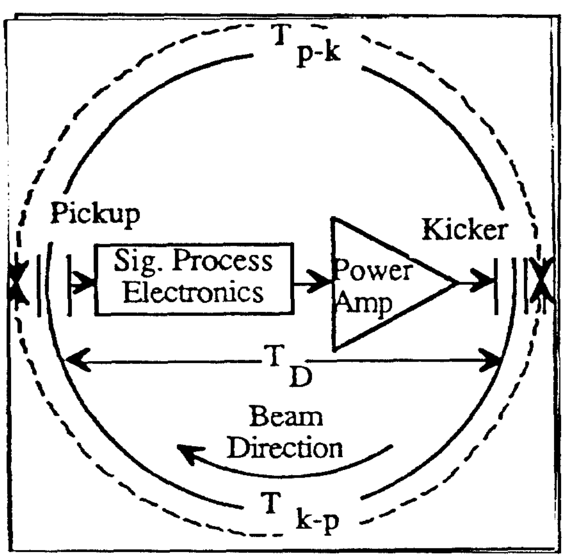

Figure 1. Simple schematic of a damper system.

II. NARROWBAND VS. WIDEBAND

The frequencies of the coupled bunch modes are located around the rotation harmonics, and the number of coupled bunch modes equals half of the RF buckets [1]. A narrowband damper damps one coupled bunch mode, while a wideband damper damps all coupled bunch modes. There are advantages and disadvantages to both.

A. Noise Power and Processing Requirements

The gain requirements of a damper systerm are determined by the instability growth rate [2]. With the gain set, the power requirements of the damper are determined by the noise power, and the power of rotation and RF harmonics on the output signal. The high power, linear, RF amplifiers are the most expensive part of the system, so the cost of the system becomes proportional to the output power required.

A narrowband damper blocks all frequency components outside the range of the single coupled bunch mode frequency. This makes the noise power very small and reduces the amount of output power required, but it only damps one mode. If more than one mode is unstable, multiple narrowband dampers must work in parallel. This not only increases the output power requirements, but it also increases the processing cost. A separate processor will be needed for every unstable mode.

Only one wideband damper processor is needed to damp all of the coupled bunch modes, but the noise power is much greater than in the narrowband system. Consequently, the wideband damper will require more powerful amplifiers than the narrowband damper for a given damper gain.

If there areonly a few unstable coupled bunch modes, a few narrowband systems would be the most cost effective. But, if there are many unstable coupled bunch modes, a wideband system would be most cost effective by reducing processor costs.

B. Phase Error and Delay

The RF accelerating voltage in the Booster must ramp from a frequency of 30MHz to 53MHz in a cycle time of 33ms, and the non-linear frequency ramp has a peak slope of 2GHz/s near the beginning of the cycle. The revolution period varies from 2.8μs to 1.59μs. To maintain feedback on the proper bucket, the processing system must handle 1.21μs of delay change quickly.

An error in delay from pickup to kicker will have a greater effect on the wideband damper than the narrowband damper. The narrowband damper sees the error in delay as a phase shift which is easily compensated. An error in delay for a wideband damper may cause a reduction in gain for higher frequency modes or even drive them unstable.

III. WIDEBAND TRANSVERSE DAMPER

The Fermilab Booster uses a directional stripline pickup to detect the transverse error signal for the damper. The

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signals from the two plates (top and bottom for vertical; inner and outer for horizontal) are combined in a 180° hybrid. The difference signal is processed, split with another 180° hybrid, amplified, and sent to a directional stripline kicker. The processor must maintain the proper phase relationship, bucket offset, and common mode rejection for effective damping.

A. Timing and Delay

Maintaining proper bucket delay is one of the most difficult problems in designing a wideband damper system for accelerating beam. The revolution period gets shorter as beam accelerates, and the total electrical delay from pickup to kicker must match the beam transit time. One way around this problem is to sample the beam digitally and delay the digital signal for a number of clock pulses. The system designed for the Booster is shown in Figure 2.

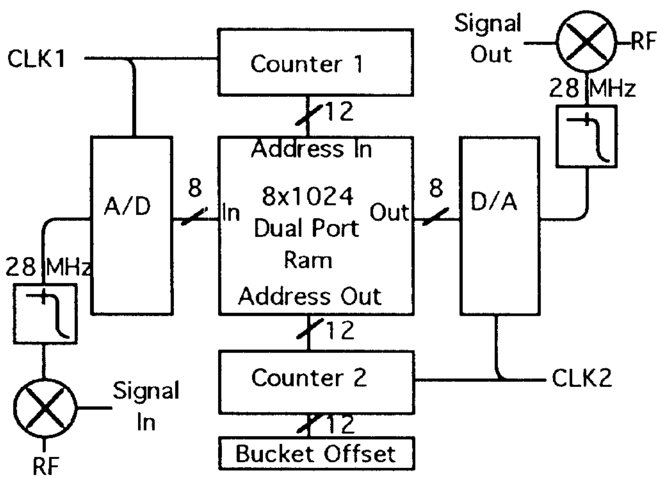


Figure 2. Digital Delay Block Diagram

The beam signal is mixed with the RF frequency, filtered, and enters an A/D converter. From the converter, the data is stored in a fast dual port memory at the address specified by the top counter. The data is then sent to the D/A converter when the bottom counter matches its memory address. The difference in value between the two counters is the bucket delay. The signal from the D/A is filtered and mixed with the RF frequency before it is sent the kickers. Mixers are required because of the frequency response of the pickup and amplifiers.

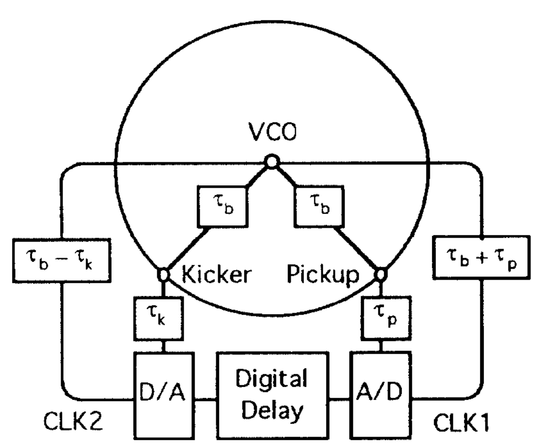
Each of the clock signals is tied to the Booster VCO which must be phase locked to the beam. The signal will be sampled at the exact frequency needed to damp all of the coupled bunch modes according to Nyquist sampling.

As long as the initial bucket delay is set correctly, taking into account beam velocity and fixed delay, the digital system will remain locked to the beam and provide proper bucket delay. Figure 3 shows the timing conditions for the system. As the beam accelerates, more of the bucket delay is stored in the fixed cable delays, τ_p and τ_k. The bucket delay of the digital delay must be reduced. Because of the difference in delay from the VCO to the A/D trigger and the D/A trigger, an increase in frequency will trigger the D/A counter more than the A/D counter according to:

$$\int_0^t f_{rf}[t' + \tau_k]dt' - \int_0^t f_{rf}[t' - \tau_p]dt' \qquad (1)$$

The number of buckets stored in the fixed delay increases by the exact same amount, so the bucket delay stays matched.

Another possibility for a digital delay is a FIFO memory. This method works very well for storage rings and ultra relativistic accelerators, but it runs in to problems with sweeping accelerators because of its fixed memory length. Even a FIFO with an adjustible pointer will have trouble when the D/A tries to read a signal at the same time the A/D is shifting the memory. The A/D can write to the dual port memory while the D/A simultaneously reads from it, giving the dual port memory more flexibility than the FIFO.



τ_b = Delay from VCO to Beam
τ_k = Delay from D/A to Kicker
τ_p = Delay from A/D to Pickup

Figure 3. Transverse Damper Timing Diagram

B. Noise Power

Because the system is wideband, the noise power is much higher than for a narrowband system. Also, the noise floor is increased by the digitization noise of the system[3]. The A/D converter is 8 bits wide and will have a dynamic range of 48dB.

This transverse damper system has two features which suppress fundamental frequencies. First, the system uses the difference signal from a stripline pickup. Ideally, the pickup would only detect changes in displacement and cancel out all common mode signals. Second, the sampling process of the digital delay filters out all of the RF harmonics of the signal.

IV. NARROWBAND LONGITUDINAL DAMPER

The Booster longitudinal damper uses the same stripline pickup used by the transverse damper, but it uses the sum of the signals from the plates instead of the difference. The phase of this signal is compared to the phase of the RF, processed, amplified, and sent to a wideband cavity. In the case of the narrowband damper, the processing must filter out a single coupled bunch mode frequency, and track that frequency throughout the cycle[4].

A. Mode Tracking

The frequency of a coupled bunch mode is a linear function of the RF frequency. A direct digital synthesizer creates a sine wave with a frequency which is some rational number less than 1 times its input frequency. Thus, a direct digital synthesizer is perfect for tracking the coupled bunch mode frequency with a sweeping RF.

Figure 4 shows the layout of the Booster narrowband longitudinal damper processor. The processor is a tracking notch filter, where the notch is located at a revolution harmonic. The revolution harmonic, around which damping occurs, is chosen by the user through the DDS. An equation for determining the DDS ratio is:

$$\text{DDS ratio} = \frac{\text{mode\# + harmonic \#}}{\text{harmonic \# x 4}} \quad (2)$$

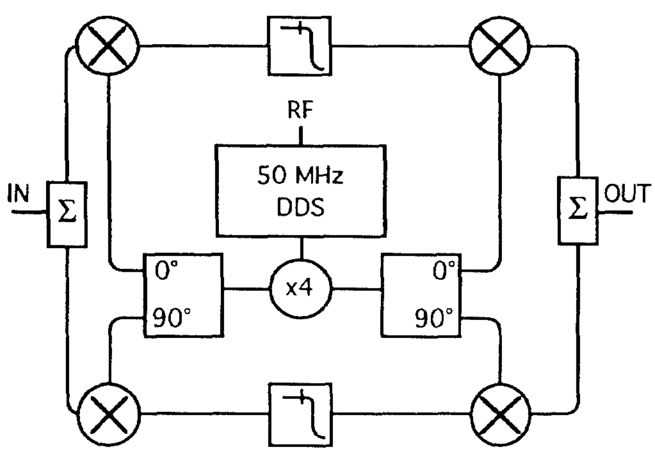


Figure 4. Narrowband Longitudinal Damper Processor

This ratio can be set using any terminal emulator with an RS232 port. A frequency quadrupler is used to track modes at the peak response of the pickup. The filters in the baseband portion of the processor have a bandwidth of 5 kHz and this keeps the noise bandwidth much lower than the wideband damper. The low bandwidth also rejects the fundamental frequency except for the leakage through the mixers.

Results from the narrowband damper are shown in Figure 5.

V. WIDEBAND LONGITUDINAL DAMPER

The wideband longitudinal damper system tested in the Booster is an energy damper. It uses the horizontal stripline detector in difference mode at a high dispersion point. The energy signal is then processed, amplified, and sent to a wide bandwidth cavity. A wideband longitudinal damper requires almost the same kind of processing that a wideband transverse damper requires. The wideband system has not been tested with the digital delay, however. Instead, a system of switching cable delays was used which did not provide adequate common mode suppression for effective damping. This test led to the design of the digital delay, and future designs of the digital delay are planned for the longitudinal damper.

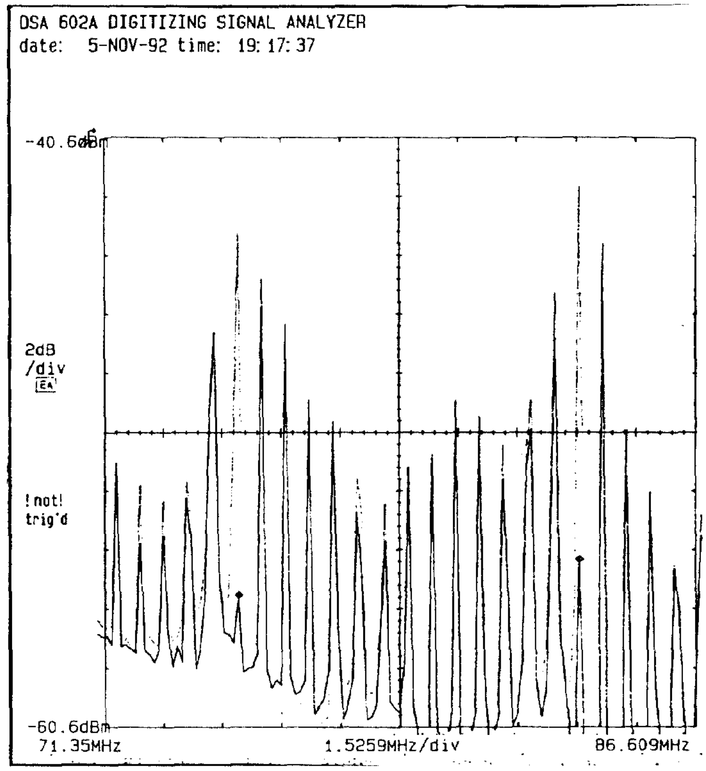


Figure 5. Effect of dampers on coupled bunch mode #35. RF = 52.8MHz, DSA ratio = (35 + 84)/(4*84)

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

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