TRANSVERSE BEAM DAMPERS FOR THE FNAL ANTIPROTON RINGS

J. Petter, J. Marriner, J. McCarthy

Fermi National Accelerator Laboratory*

P.O. Box 500, Batavia, IL 60510

Abstract

A wide band damper system has been developed for the Fermilab Antiproton Source. The system includes both forward and reverse beam direction damping in the Accumulator and forward only in the Debuncher. The system is currently used to damp coherent instabilities in the Accumulator during antiproton accumulation and extraction. The Damper system is also useful as a diagnostic tool. This paper will include some details about the design of the system hardware. Specifically included will be the design of the beam pickup preamplifiers, a correlator notch filter and 300 Watt 180° power splitters. Also included will be measurements made to verify the system is working properly.

Introduction

Very simply the damper system senses the beam wobbling (transverse coherent instabilities) in a pickup, amplifies that signal, delays the signal to match the beam transit time and corrects for the wobble with a kicker.

There were two main design goals for the damper systems. First, to damp coherent instabilities during antiproton accumulation and extraction. Second, to use the system as a flexible diagnostic tool.

For simplification only the Accumulator forward damper system will be explained in detail. A short statement at the end will explain how the other systems differ.

General System Specifications

Frequency Response: The damper system must operate down to the lowest betatron sideband in the ring. In the Accumulator this is ≈240Khz. The upper frequency limit must be the maximum frequency at which someone may want to do diagnostics. The maximum frequency was chosen to be at least 80Mhz because the resonant schottky pickups work at this frequency.

Signal Selectivity: All the information about transverse beams is contained in the betatron sidebands. [1], [2] The signals at the harmonics of the revolution frequency contain no useful information for damping. During extraction, these longitudinal signals are much bigger than the betatron signals. Since the kicker is driven differentially, the longitudinal signals will have almost no effect on the beam. Being large they can cause saturation of components. It is preferred that these longitudinal signals be small compared to the betatron sideband signals in order to limit the system's required dynamic range.

Gain: The system gain must be at least enough to damp the beam but not so much that the noise from the preamp heats the beam.

Phase Response: The phase of each component of the system must be linear (pure delay) over the frequency band of the system so that the total system can be phase matched to the beam transit time.

Linearity: The system must be linear so that its effect on the beam is well understood. Large nonlinearities particularly 3rd and 5th order will cause betatron sideband mixing, the effects of which are hard to predict.

Power: The system must have enough power to heat the beam in ≈10,000 revolutions for diagnostic applications such as aperture studies.

Pickup and Kicker placement: The pickups and kickers must be approximately some odd multiple of 90° in betatron phase from each other. This is because the pickup senses beam position errors and the kicker can only effect the beam angle. In addition the pickups must be in locations of low dispersion to help avoid coupling to longitudinal modes.

Preamplifiers and Pickups

The pickups used are .5 meter long, 50Ω, 90° radial, stripline type as described in [3]. The length of the pickup limits its frequency response to about 225 Mhz. A high input impedance differential preamp was chosen to improve the low frequency signal to noise ratio and get a flat pass band. The pickup is back terminated for high frequencies to flatten the phase response around the 1/4 wave frequency (150Mhz). This termination (see figure 1) was capacitively coupled so it would

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ACCUMULATOR VERTICAL DAMPER SYSTEM BLOCK DIAGRAM

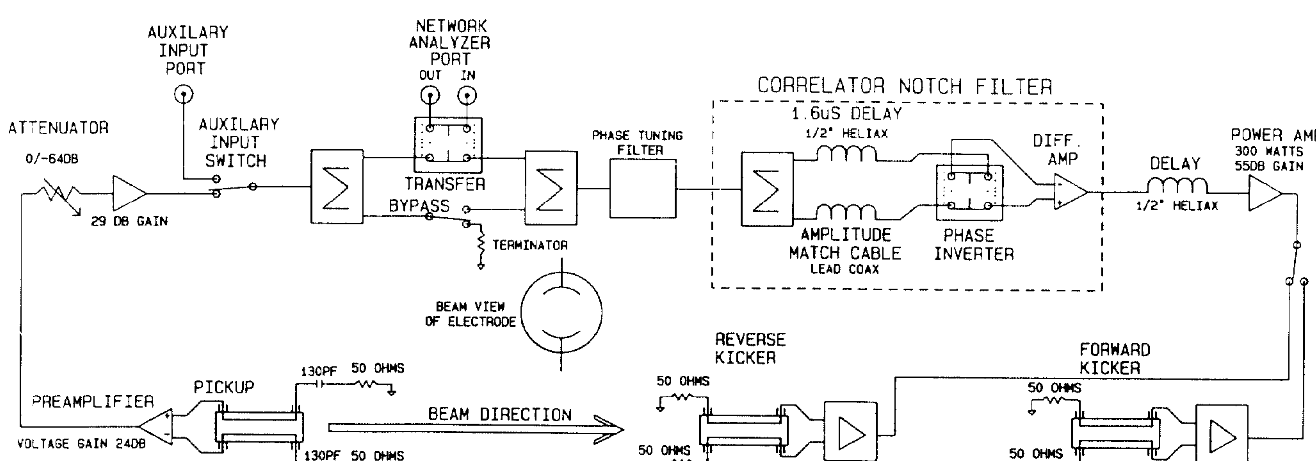

Figure 1

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not destroy the low frequency response. This added capacitance increases the pickup capacity at low frequencies and lowers the pickup sensitivity. The additional capacitance was needed to limit the common mode signals seen by the preamp during extraction of large batches of antiprotons. The increased pickup capacity also lowers the required input impedance needed in the preamp to get the low frequency response. The low end frequency corner is given by $F=1/2\pi RC$. Where R is the input resistance of the preamp ($\approx 5k\Omega$) and C is the total capacitance of the preamp input, pickup, termination and the cable ($\approx$200pF).

During extraction of Pbars there are large common mode (unwanted revolution harmonic) signals at the input of the preamp. These signals could be as large as 8 volts peak to peak. The preamp must still be able to measure small differential mode signals at this time. So the preamp was design to have a very high common mode rejection ratio (See Figure 2) and an input circuit that does not saturate for these large common mode signals. In addition, if the beam does not go through the exact electrical center of the pickup some of the revolution harmonic signal will be differential and pass through the preamp. For this reason each of the pickups are on motorized stands so they can be centered in the beam. Due to the resolution of the motorized stands some of the revolution harmonic signals get through, so the amplifier had to be designed to handle the increased dynamic range.

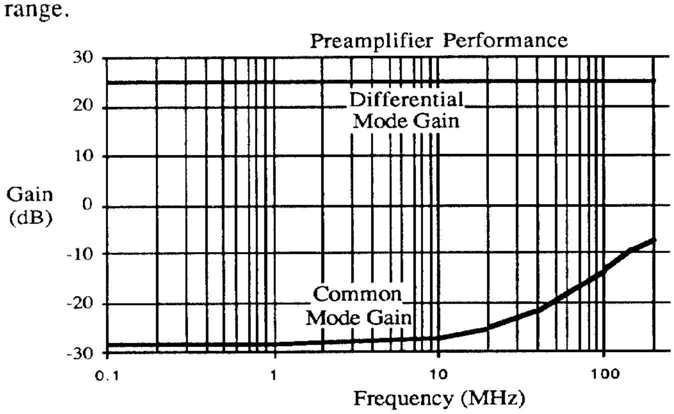

Figure 2

Notch Filter

The notch filter was needed in the damper system to reject excess revolution harmonic signals so that the power amplifier would not need to have extra head room to keep from saturating. The notch filters are electrically similar to the Pbar Stocastic Cooling Superconducting Notch Filters described in [4]. The 0° splitter used is a commercial resistive type. The delay line is 1/2" Heliax cable. The attenuation and dispersion of this cable changes quite a bit due to the large change in skin depth over this frequency band. This was matched by a 12 meter piece of lead coax for the compensation line. The lead coax is the same cable used in the Pbar Stocastic Cooling Superconducting Notch Filters. To obtain a lossy line it is used at room temperature. The difference of the signal between the delay line and compensation line is taken by the difference amplifier developed for the preamp. For this application the preamp has 50Ω across its inputs. This was done because no commercially available 180° splitters could be found that would cover the needed frequency band (70Khz to 225Mhz). An attenuator was added in series with the delay line to match attenuation of the lead coax at low frequencies. The value of attenuation and the cable lengths where chosen to make the losses in the two legs of the filter match at the first harmonic of the revolution and at the 84th harmonic of revolution (the RF frequency). All notches are better than 30 dB from 628Khz to 200Mhz. At the two tuned notches (628Khz and 53Mhz) rejection is better than 50 dB.

Kickers

The kickers utilize the same type of electrodes as the pickups except that they have a larger aperture due to their location in the lattice. The kickers are configured as basic terminated 50Ω 1/4 wave loops (see figure 1). Because the wave velocity in the kicker (β=1) is approximately equal to the beam velocity (β=0.995), the beam gets an equal kick from the electric and magnetic fields (if the directions are correct). The kick due to the electric field for small angles is approximately $Ekick/volt=(L/2r*\beta^2*E)$ where: L is the length of the kicker, 0.5m, r is the radius of the kicker, 0.038m, and E is the energy of the beam, 8GeV. Thus, the total kick, $1.6*10^{-9}$ radians/volt, is twice the kick from the E field alone. The beta function (β) at the kicker is 20m so it takes $2\,r\,/\,(\,2^{1/2} * Ekick * \beta\,) = 1.7*10^6$ volt turns to heat the beam to the full aperture of the kicker. Of course the kickers are not the aperture limit of the machine but this gives a number to work with. In order to heat the beam in 10,000 turns 177 volts peak is needed across the kicker plates. This corresponds to an RMS power of 156 watts into the splitter.

Power Amplifiers and Phase Compensation

It was decided that the minimum power needed would be 100 watts. The optimum power amplifier would have linear phase response from 100Khz to 225Mhz and drive 100 Watts into 50Ω. The best we could do was an ENI 3200L which claimed to have flat amplitude response from 250 Khz to 150Mhz and linear power to 200 watts. After measuring one, it was found to have amplitude response down less than 150Khz, but the phase response was off from linear by more than 120 degrees at 240Khz. Its phase response acts as though there are 6 poles at $\approx$100Khz. A commercial power amplifier was desired in order to keep the cost of the system down. So, the frequencies from 150Mhz to 225Mhz were sacrificed, and a phase compensation circuit was designed to straighten out the low end phase.

The phase compensation circuit is a unity gain amplifier at frequencies above 1Mhz and has a tuned gain peak just below the lowest betatron sideband (240Khz). This gives a phase response that compensates for the phase of the power amplifier plus the phase of all the other less significant low frequency poles in the system. This solution causes the gain of the total system to be higher ($\approx$10 dB) at the low end.

180° Power Splitters

A commercial power splitter that could handle the full power of the power amplifier and cover its frequency range could not be found, so one was developed. After much tinkering a design was found that split 300 Watts into 2 ports 180° out of phase. Its frequency response is 70Khz to 200Mhz +/- 1dB. The splitter is made of two transformer sections each of which is made from 1.5cm diameter ferrite toroids. The first section is a 50Ω to 100Ω transformer. The second section is a ballen to convert to 2 out of phase 50Ω ports. Its construction is twisted wire transmission lines similar to those in [5]. To improve its power dissipation the box containing the toroids is filled with oil.

300 Watt 180° Power Splitter Simplified Schematic

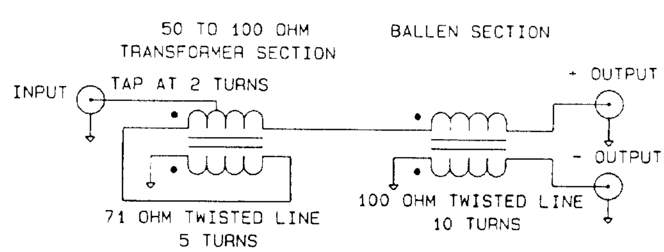

Figure 3

System Tests

First the system had to be phased with the beam; this was done by connecting the network analyzer as shown in figure 1. Then a signal was swept across each betatron sideband to measure the relative phase of the signal that returned to the input of the network analyzer. The relative phase should be 180° ± 45° at the center of each sideband in which the loop gain, including the beam, is over unity. Note the pickup gain goes up with beam intensity and the losses go down in the beam part of the loop as beam intensity increases (i.e. the beam becomes less stable).[1],[2] Because the beam stability in general should improve with frequency, it helps to have the system phase correct for as wide a band as possible.

The best proof that the system was actually working came when the system failed. A connection came loose in the horizontal damper system causing the system gain to go to zero. There were $2*10^{11}$ antiprotons in the core. The authors noticed that the beam emittance had grown. In fact the horizontal emittance had grown by more than two times and the vertical emittance had also grown by a small amount (see figure 4). At closer examination the horizontal emittance was growing and cooling periodically with a period of approximately 15 minutes. This mean level of emittance was more than twice what it had been. When the damper system was repaired the emittances in both planes recovered to a lower and stable level (see figure 5).

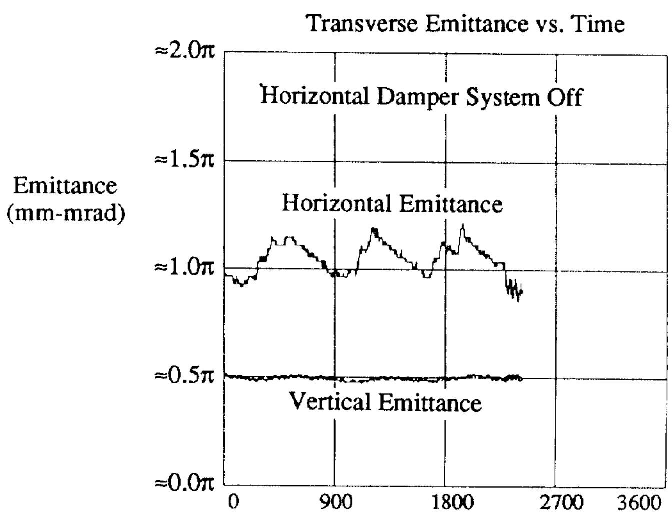

Figure 4

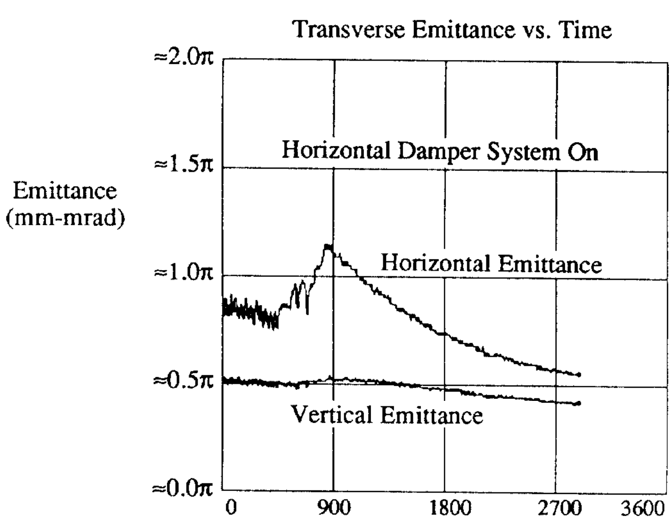

Figure 5

Using the Damper for Diagnostics

The damper system has the capability of transversely exciting the beam from 150Khz to 150Mhz and measuring transverse signals from 70Khz to 225Mhz. This makes it capable of doing many different types of beam studies, including:

Aperture Studies: The damper systems in both machines have been used to heat proton beams so they fill the aperture. During heating, loss monitors are studied to help find the devices that limit the aperture. After heating, scraper scans are made to measure the aperture.

Studying Transverse Instabilities and Beam Impedance: In this study the damper system is configured as in the phasing measurement above. The network analyzer measures the complete complex transfer function across the band rather than just the phase at the center of the band.

Studying Transverse Coupling: This involves putting signals on kickers in one plane and looking at signals coming from the pickups in the other plane.

Measuring Tunes for Low Beam Intensities: When the Accumulator was turned on after the last shut down the machine would only accept a small amount of beam. The beam was too little to be detected by the transverse resonant schottky pickups.Using the network analyzer as a synchronous detector a signal from its output was sent to the damper kicker. The analyzer input was connected to the schottky pickup. The analyzer was then set to plot the amplitude of the signal at its input while sweeping over the frequencies which the schottky pickup is resonant.

Other systems

The reverse direction damper system uses the same pickups as the forward direction system but different kickers. Otherwise the reverse direction system is the same as the forward system.

The Debuncher damper system is not presently used as a damper, but is used from time to time as a diagnostic tool. The lowest sideband in the Debuncher is at 110Khz. Thus, the power amplifier and phase compensation used in the Accumulator system will not work. For this reason the Debuncher system uses a ENI 2100L power amplifier which has a useful band from 10Khz to 12Mhz and will supply 100 watts into 50Ω. This system also does not have a notch filter; it was never really intended to be used in a closed loop.

Conclusions

The Antiproton source damper system has been in use continuously since its installation.It has been demonstrated that the damper system helps provide a high density beam to the Tevatron for colliding beam physics. There are still many interesting and useful studies to be done when time permits.

References

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