FERMILAB-CONF-05-167-AD

FERMILAB RECYCLER DAMPER REQUIREMENTS AND DESIGN

J. Crisp[#], M. Hu, V. Tupikov,   Fermilab, Batavia, IL 60510, U.S.A.

Abstract

The design of transverse dampers for the Fermilab Recycler storage ring is described. An observed instability and analysis of subsequent measurements where used to identify the requirements. The digital approach being implemented is presented.

INTRODUCTION

The Recycler transverse damper will maintain stability during a store by actively reducing the transverse impedance. The system uses 30 cm long split plate style bpms (beam position monitors) connected through short cables to high impedance low noise preamplifiers located in the tunnel. A digital notch filter removes harmonics of the rotation frequency and passes the betatron sidebands. Stripline kickers driven through 100 watt amplifiers correct the beam. The bandwidth covers the lowest 220 rotation harmonics.

TRANSVERSE BEAM IMPEDANCE

At low frequency, the beam impedance is dominated by the skin effect losses in the stainless steel beam pipe. The estimated value for the Recycler transverse impedance at ½ the rotation frequency is 18 MOhm/m. For the highest intensity and worst case running conditions the necessary damper gain for beam stability is 0.5 urad/mm. Space charge, the effect of the beam's charge on itself, also plays a significant role.

The transverse beam impedance of the recycler was measured by comparing the transfer functions taken at two different intensities. Their difference is attributed to the beam current acting on the machine impedance. The results were consistent with calculated values, however, accuracy was poor at the beam intensities used.

POSITION MEASUREMENT

A transverse damper system measures beam position and changes the beam angle. Optimum performance requires a 90° betatron phase advance between the bpm and the kicker location. In the Recycler, two bpm's separated by about 90° in betatron phase will be combined to simulate the ideal phase advance.

Recycler split tube bpm's are used. An elliptical tube 30 cm long is sliced at an angle to form two electrodes for either a horizontal or vertical detector. The capacitance of the electrode is 47 pf and the capacitance of the cable connecting the preamp is 45 pf. The 300 KOhm preamp input impedance and 102 pf bpm and cable capacitance determine the 20 KHz low frequency limit of the system. The lower frequency limit was chosen to provide acceptable phase error at 36 KHz, the fractional tune (0.4) times the rotation frequency (90 KHz). Taking into consideration the 7pf plate to plate capacitance, the position sensitivity of the bpm's are 33mm horizontal and 62mm vertical.

$$\frac{V_{plate}}{I_{beam}} = \frac{1}{2}\frac{l}{\upsilon}\frac{1}{C_{total}} = 5\Omega \qquad for\ \ f > 20KHz$$

$$Hor\ \ pos = \frac{A-B}{A+B}K \qquad K = \frac{33mm\ Hor}{62mm\ Ver}$$

$$\left(A, B\ are\ the\ signals\ on\ the\ two\ bpm\ \ plates\right)$$

The preamplifier consists of a low noise input op-amp (AD8045) and 50 ohm driver (AD8009). The equivalent noise density at the input is 11nV/√Hz. For 6e12 particles in 1.6usec the equivalent vertical position noise is 2.6nm/√Hz. With a 20MHz bandwidth, to avoid aliasing with the sample rate, the total equivalent position noise is 0.72um rms.

$$Ver\ \ pos\ noise = 62mm\frac{\sqrt{2}\left(11\frac{nV}{\sqrt{Hz}}\right)}{2\left(5\Omega\ \ 0.6Amps\right)} = 2.6\frac{nm}{\sqrt{Hz}}$$

$$0.72\mu m\ rms = 2.6\frac{nm}{\sqrt{Hz}}\sqrt{20MHz}$$

Dividing the difference by the sum can cause problems at low intensities. Exploiting the fact that lower damper gains are acceptable for lower intensities, only the difference signal (A-B) is used in the feedback path.

DIGITAL FILTER

A second generation VME board is being constructed for use by the damper systems in both the Main Injector and Recycler at Fermilab. The board has four 12 bit 212 MSPS ADC's (AD9430), four 14 bit 600 MSPS DAC's (AD9725), and one Altera Stratix (EP1S40) FPGA (Field Programmable Gate Array). A phase lock loop inside the Stratix will be used to produce 212 MHz from the 4th harmonic of the Recycler low level rf system clock to synchronously clock the ADC's. Separate boards will be used for the horizontal and vertical systems.

One ADC will be used for each of the two positions (A-B) and one will be used to measure the intensity (A+B). The intensity information may be used as a "squelch" by setting the output to zero for low beam currents. The remaining ADC can be used for testing such as measuring the open loop transfer function, or the closed loop response of the system. Three DAC's will be used, one for each of the stripline kicker plates, and one for testing. Separate DAC's will allow accommodating for

---

* Operated by Universities Research Association Inc., under contract with the U.S. Department of Energy.

[#] crisp@fnal.gov

differences in amplifier response or stripline plate impedance.

CIC (Cascaded Integrating Comb) filters will be implemented inside the Stratix for each of the ADC's to low pass filter the input and to decimate the data to a more manageable rate of 53 MHz. After combining the two bpm position signals a pipeline delay and an FIR filter provide two key functions:

1. The delay through the direct path from detector to kicker must result in the error from any given particle being used to kick that particle.
2. The delay through the FIR filter tap should be exactly one turn to produce notches at harmonics of the revolution frequency.

Variable gains will be used to balance the contributions of the two bpm's to simulate the desired betatron phase. Additional taps with delays that are multiples of one turn can be used to shape the pass bands of the comb filter and provide a better phase response. Time gating of the damper will also be required to avoid problems during injection, coalescing, and extraction.

POWER AMPLIFER AND KICKER

Kalmus, 100 watt, 10KHz to 230MHz, solid state, air cooled, amplifiers were purchased. The power amplifiers represent about half the cost of the system. The striplines are 1.4 meters long and have an 11 cm plate separation. The beam momentum is 8.9 GeV/c.

$$kicker\ gain = 2\frac{l}{g}\frac{\sin\frac{\omega l}{\upsilon}}{\frac{\omega l}{\upsilon}}\frac{1}{P} \approx 2.9\frac{nRad}{V} \qquad \omega < 20MHz$$

Two amplifiers will provide a maximum plate to plate voltage of 200 Volts. For the 1uRad/mm damper open loop gain, a 0.6mm position error will produce the maximum kick.

$$\max\ pos = 200V\left(2.9\frac{nRad}{V}\right)1\frac{mm}{\mu Rad} = 0.6\ mm$$

DAMPING RATE

For low beam intensities, machine impedance and instabilities can be ignored. Under these conditions, the 1/e damping time constant is just one over the open loop unity gain frequency of a simple feedback model. The factor of ½ in the block diagram comes from the time average of the sinusoidal betatron oscillation being measured.

$$for\ \ G = \frac{1\mu Rad}{mm}, \quad \beta_{\det} = \beta_{kick} = 20m, \quad \Delta\psi = 90°$$

$$N_D = \frac{2}{G\sqrt{\beta_{\det}\beta_{kick}}\ \sin\Delta\psi} = 100\ turns$$

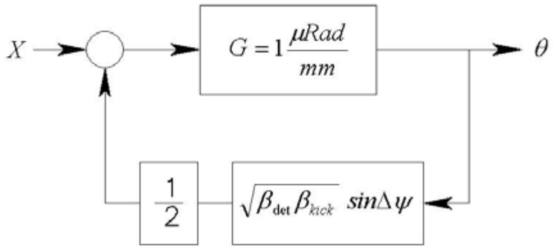

Figure 1: Simple block diagram of damper feedback loop.

NOISE AND EMITTANCE GROWTH

The 12 bit ADC has a SINAD (signal to noise and distortion) of 64db. Considering the decimate by 4 CIC filter and a single tap FIR comb filter, the digitizing noise is 2.2um rms for a ±5mm position range.

If the beam closed orbit is not at the electrical center of the bpm, harmonics of the rotation frequency will be induced in the position signal. The purpose of the FIR comb filter is to reduce this signal before it reaches the kicker and cause emittance growth. The 12 bit ADC and decimate by 4 CIC filter provides 70db of attenuation at the rotation harmonics. A 5mm closed orbit error will be attenuated to an equivalent 1.6um error.

The total undesired signal projected to an equivalent beam position can be estimated by adding the elements in quadrature.

$$\begin{aligned} preamp\ noise &= 0.74\mu m\ rms \\ 5mm\ closed\ orbit &= 2.2\mu m\ rms \\ ADC \pm 5mm\ range &= 1.6\mu m\ rms \\ total &= 2.8\mu m\ rms = \sqrt{0.74^2 + 2.2^2 + 1.6^2} \end{aligned}$$

The undesired signal at the amplifier output can be determined from the equivalent position errors and the kicker and damper gains.

$$\begin{aligned} amp\ output &= 2.8um\ rms\left(1\frac{\mu Rad}{mm}\right)\frac{1}{2.9}\frac{V}{nRad} \\ &= 1.0V\ rms \end{aligned}$$

The transverse emittance growth from this undesired signal is estimated below for γβ of 9.5, 20 meter kicker beta, and 90KHz rotation frequency:

$$\begin{aligned} \varepsilon\ growth &= \frac{1}{2}(\gamma\beta)\beta_{kick}\left(1Vrms\ 2.9\frac{nRad}{V}\right)^2 90KHz \\ &= 0.26\frac{\pi\ mm\ mRad}{Hr} \end{aligned}$$

This growth will be reduced with the damper feedback. However, this improvement will be small considering the 100 turn damping rate and the typical decoherence rate. The transverse emittance growth rate caused by residual gas at the low 10^{-10} torr level in the Recycler is about twice this.

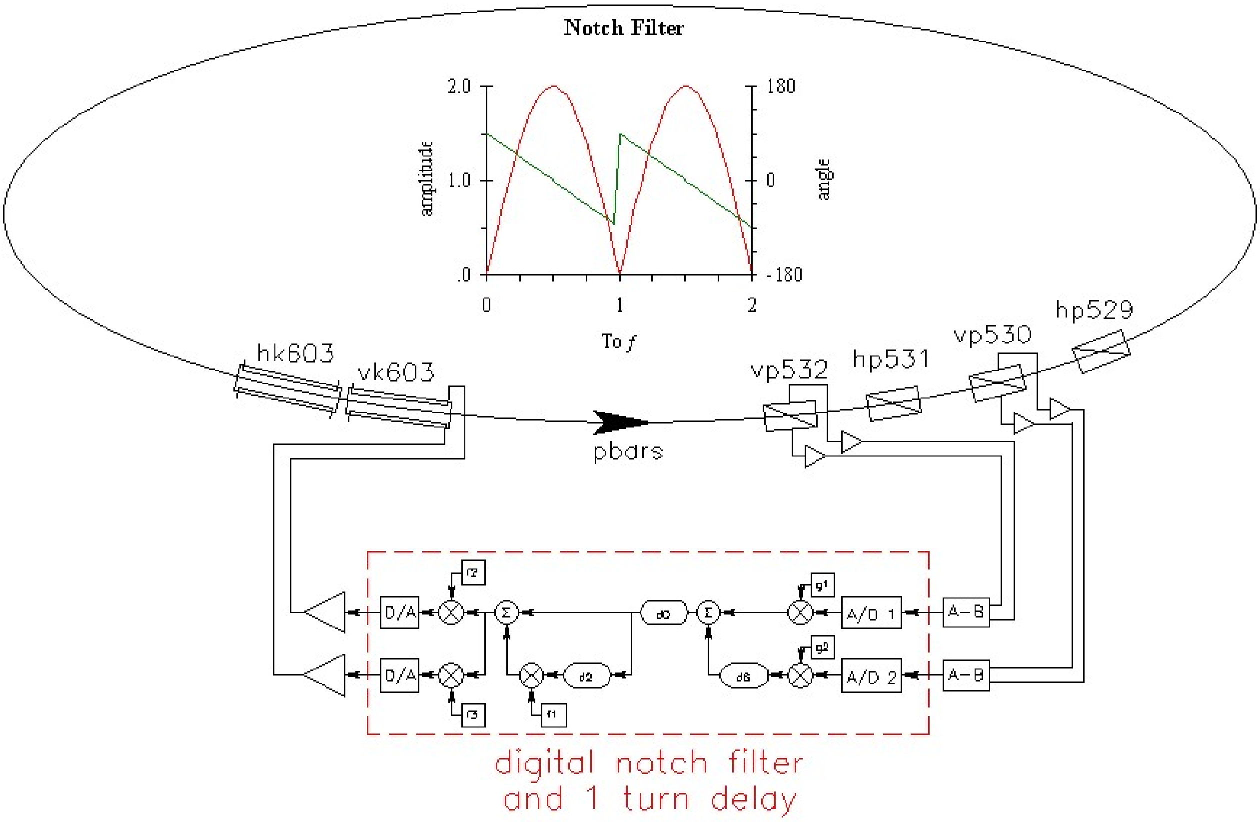

Figure 2. Simple block diagram of the vertical damper system

CONCLUSION

Landau damping by increasing the tune spread can also be used to control instabilities. For the Recycler, this leads to unacceptable emittance growth and poor lifetime. The active damper system described here offers sufficient gain to overcome the instability while maintaining small emittance growth.

REFERENCES

[1] V. Balbekov, "Transverse Instability of a Rectangular Bunch (theoretical model)", unpublished document, January 2005.

[2] D. Boussard, "Schottky Noise and Beam Transfer Function Diagnostics", Cern Acc. School, CERN 95-06, November 1995, page 775.

[3] P.J. Chou, and G. Jackson, "Beam Transfer Function and Transverse Impedance Measurements in the Fermilab Main Ring", PAC 1995.

[4] G.W. Foster, S. Hansen, D. Nicklaus, W. Schappert, A. Seminov, D. Wildman, "Bunch-by-Bunch Digital Dampers for the Fermilab Main Injector and Recycler", PAC 2003.

[5] J. Crisp, K. Gubrienko, V. Seleznev, "Stripline Detectors for Fermilab Main Injector", IHEP ACONF98.

[6] C.Y. Tan, J. Steimel, "The Effect of Noise on Transverse Emittance Growth in the Tevatron", Fermilab-TM-2121, August 2000.