FERMILAB RECYCLER DAMPER REQUIREMENTS AND INITIAL DESIGN*

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Abstract

The design of transverse dampers for the Fermilab Recycler storage ring is described. An observed instability and analysis of subsequent measurements are 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 foot long split plate style bpms 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 is 18 MOhm/m, at ½ the rotation frequency. The necessary damper gain is 0.5 urad/mm for the highest beam intensity and worst case running conditions. Space charge, the effect of the beam's charge on itself, influences this estimate.

The transverse beam impedance of the recycler was measured by comparing the transfer function taken at two different intensities. The difference is attributed to the beam current acting on the machine impedance. The results were consistent with the 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 to correct it. Optimum performance requires a 90º betatron phase advance between the position measurement and the kicker location. In the Recycler, two bpm's separated by 90º 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 of 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. This was chosen to provide acceptable phase error at 36 KHz, the fractional tune (0.4) times the rotation frequency (90 KHz). The position sensitivity of the bpm is 33mm horizontal and 62mm vertical taking into consideration the 7pf plate to plate capacitance.

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

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

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, the total equivalent position noise is 0.72um rms.

$$Ver\ pos\ noise = 62mm\frac{\sqrt{2}\left(11\frac{nV}{\sqrt{Hz}}\right)}{2(5\Omega\ 0.6Amps)}\sqrt{20MHz}$$
$$= 0.72\mu m\ rms$$

To avoid problems with position noise at low intensity, only the difference signal (A-B) is used in the feedback path. Lower beam intensities require less gain. The 20 MHz bandwidth was chosen to prevent undesired aliasing with the sample rate.

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 MHz ADC's (AD9430), four 14 bit 600MSPS DAC's (AD9725), and one Altera Stratix (EP1S40) FPGA (Field Programmable Gate Array). The VME interface will be programmed into the Stratix. A phase lock loop, also inside the Stratix, will be used to produce the 4th harmonic (212 MHz) of the Recycler low level rf system 53 MHz to synchronously clock the ADC's. Separate boards will be used to make digital FIR (Finite Impulse Response) comb filters for the horizontal and vertical systems.

One ADC will be used for each of the two positions and one will be used to measure the intensity or 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, one for each of the stripline kicker plates, and one for testing will be used.

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.

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The digital FIR comb filter must 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 tap should be exactly one turn to produce notches at harmonics of the revolution frequency.

Digitally variable gains will be used to balance the contributions of the two bpm's to simulate the desired betatron phase. Multiple turn delays can also be used in place of two bpm's to obtain near optimum betatron phase advance between the pickup and kicker. Additional taps with delays that are multiples of one turn can be used to shape the pass bands of the comb filter or to provide a better phase response.

Using separate DAC's for the stripline plates will allow accommodating for differences in amplifier response or stripline plate impedance.

POWER AMPLIFER AND KICKER

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

$$\text{kicker gain} = 2\frac{l}{g}\frac{\sin\frac{\omega l}{\upsilon}}{\frac{\omega l}{\upsilon}}\frac{1}{P} = 2.9\frac{\text{nRad}}{\text{V}}$$

Two amplifiers will provide a maximum plate to plate voltage of 200 Volts for a 0.6mm position error.

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

DAMPING RATE

The 1/e damping time constant is just one over the open loop gain.

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

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

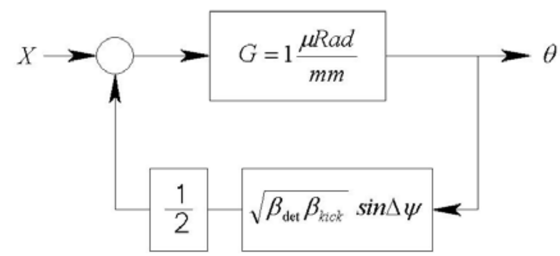

Figure 1: the schematic of the feedback loop.

NOISE AND EMITTANCE GROWTH

The 12 bit ADC (AD9430) 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 will be 2.2um rms for a ±5mm position range. The depth of the notches of the comb filter will be about 70db. A 5mm closed orbit would produce rotation harmonics that will be attenuated by 70db to the equivalent of a 1.6um closed orbit. The total undesired signal projected to an equivalent beam position can be estimated by adding the elements in quadrature.

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

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

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

The transverse emittance growth from this undesired signal can be estimated for γβ of 9.5, 20 meter kicker beta, and 90KHz rotation frequency.

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

This growth will be reduced slightly with the damper feedback turned on considering the 100 turn damping time constant and the typical decoherence rate.

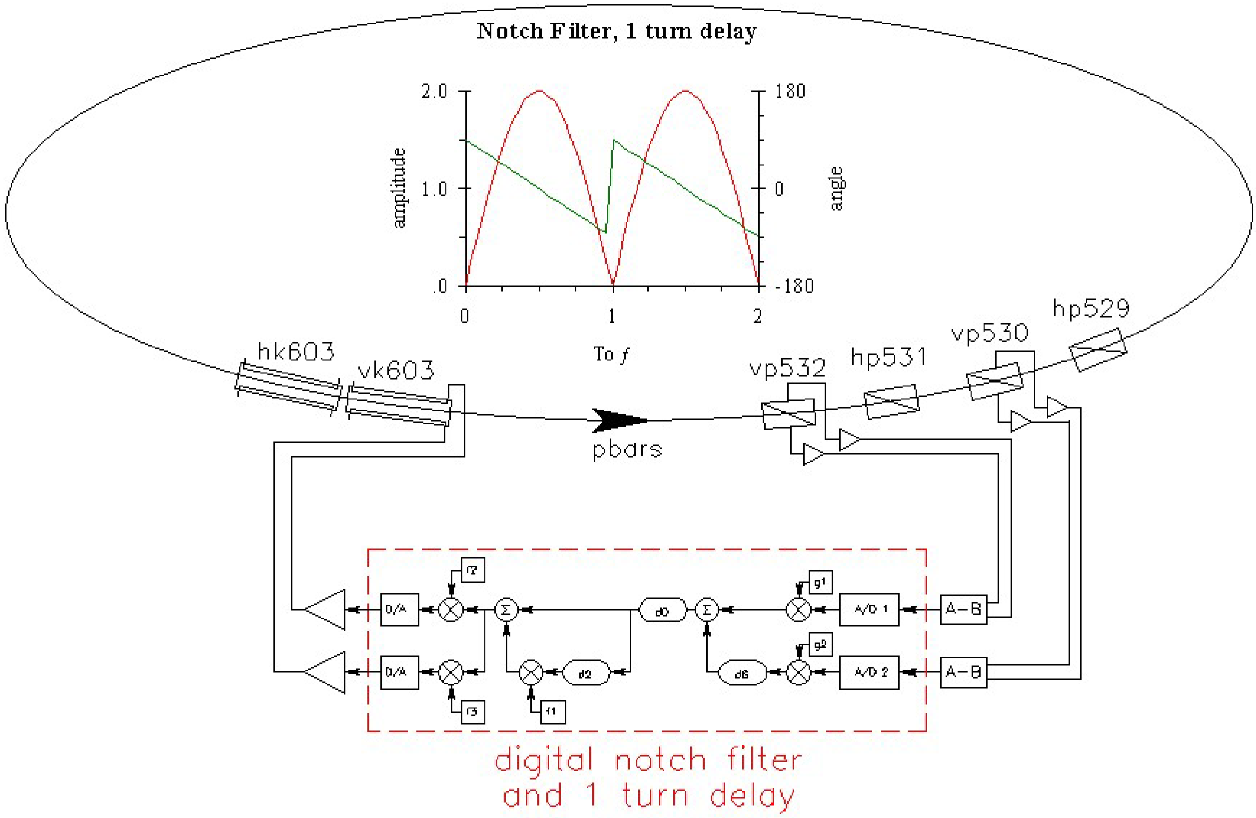

Figure 2: The schematic of the damper system.

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