PERFORMANCE OF A CORRELATOR FILTER IN BETATRON TUNE MEASUREMENTS AND DAMPING ON THE NSLS BOOSTER*

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Abstract

A "compensated correlator filter", described by Kramer, et al.[1] has been used for measurement and damping of betatron oscillations in the NSLS booster. The filter consists of a zero-degree power splitter, a 180-degree splitter, a length of 7/8" air dielectric coaxial cable, and a short length of RG-58 cable. Connected to a beam position monitor, the output of the filter is proportional to the difference in transverse position of each bunch on subsequent turns. The useful bandwidth of the filter for damping rigid bunch oscillations extends from 10 MHz to 250 MHz, in contrast with the gigahertz bandwidth requirements for stochastic cooling, for which the filter was originally proposed. Attenuation of all rotation harmonics in this bandwidth is 40-60 dB.

Introduction

The correlator filter, depicted schematically in figure 1, has been proposed as an alternative to a stub filter for stochastic cooling [1,2,3]. A signal $V(t)$ entering the 0-degree splitter is fed to two transmission lines whose propagation delay times differ by an amount T . The signal and its delayed duplicate are then subtracted using a 180-degree combiner. Ideally, the output is proportional to $V(t) - V(t-T)$. If T is adjusted to be the rotation period of a particle beam in a synchrotron and $V(t)$ is a signal from a beam position monitor, the correlator filter should give no output for signals which repeat with period T . Thus a correlator filter can be used to reject any signals except those from off-energy particles or from transversely oscillating particles. This is essential to prevent overloading of an active damping system by signals from beam motions which require no correction. This filter was originally proposed for use in stochastic cooling dampers, for which response in the gigahertz range is relevant. This paper reports the application of a correlator filter to monitoring and damping of horizontal betatron oscillations of a bunched beam in the NSLS booster synchrotron [4]. For this purpose, signal bandwidth to 300 megahertz is more than adequate. Optimization of filter performance is easily done based on frequency-domain bench measurements. The performance of the optimized filter is sufficiently close to ideal that one can describe its action on a beam position signal in the time domain: if the input is a train of pulses proportional to the position of each beam bunch, the output is proportional to the difference in position of each bunch on subsequent turns; this output can be amplified and used to kick the beam. Damping results for the correct phase advance between monitor and kicker, which can be calculated simply using the transport matrix formulation of betatron damping following Kheifets [5].

Bench Measurements and Performance

The correlator filter built for the NSLS booster consists of a 105 nanosecond length of RG-318 cable (Andrew HJ5-50), a 10 nanosecond length of RG-58 cable, an Anzac T-1000 splitter and an Anzac H-81-4 180-degree combiner. The attenuations and delays of these components were compared in the frequency range 10-200 MHz using a Hewlett-Packard 3577A network

analyzer. Figure 2 shows the output of one side of the T-1000 splitter, normalized to the output of the opposite side. The upper trace shows amplitude and the lower trace shows phase. We see that one output matches the other to within 0.01 dB and 0.1 degree at 0 MHz, and differs by -0.02 dB and -0.3 degree at 200 MHz. If all other components were perfect, the notches would be at least 53 dB deep. Figure 3 shows the same measurements for the H-81-4. The amplitude imbalance ranges from -0.25 dB at 10 MHz to -0.17 dB at 200 MHz. The phase changes from +2.0 degrees to -0.5 degrees in the same range. The phase error is acceptable, but the amplitude error would limit notch depth to 33 dB if not corrected. Figure 3 shows the amplitude (upper trace) and phase of the RG-58 cable relative to that of the RG-318 cable. The difference in lengths measured with the network analyzer was 95.53 nanoseconds, 0.01 nanosecond shorter than the booster rotation period. The length of the RG-58 cable was adjusted to 10 nanoseconds so that its attenuation combined with the slight imbalance of the T-1000 would match the H-81-4 to within about 0.04 dB and give 48 dB notches. The irregularities in attenuation ratio are caused by several connectors and adaptors in the RG-58 cable. The performance of the complete filter is shown in figures 5 and 6. The spikes in figure 5 are the rotation harmonics of the booster beam received from a "sugar scoop" capacitive pickup electrode. The spikes in figure 6 are the same signal passed through the filter. The variations in notch depth are in correspondence with the irregularities of figure 4. In particular, the especially good rejection of rotation harmonics at 95 MHz and 148 MHz are caused by the extra attenuation in the RG-58 cable at these frequencies, which match more accurately the asymmetry of the H-81-4. The notch depths have not changed by more than a few dB in the past months.

Betatron Damping

The betatron damper was constructed using a 5:1 transformer to take the difference of signals on two plates of a pickup electrode and match to the 50 ohm impedance of the filter. The transformer and two 48 picofarad pickup plates give a time constant of 6 nanoseconds. The output of the filter was amplified 66 dB and applied to the beam with a stripline kicker. The active shunt impedance of this arrangement is about 200,000 ohms/meter, and the damping time constant was 280 microseconds, or 2,900 turns. The choice of betatron phase advance between monitor and kicker was made by writing a matrix equation for the action of the damper on the beam. We will define (X, X') to be the phase space coordinates of a bunch at the kicker corrected by the feedback system and correlator filter, and (X_0, X'_0) are the canonical coordinates at the same location but on the previous turn. M is the transport matrix for a full turn of the ring starting from the kicker, g is the feedback system gain, and K is the transport matrix from the kicker to the beam position monitor. Without feedback, we would have

$$\begin{bmatrix} X \\ X' \end{bmatrix} = M \begin{bmatrix} X_0 \\ X'_0 \end{bmatrix}$$

MASTER

If one simply connects the amplified pickup electrode signal to the kicker, X' would be changed by an amount proportional to the beam displacement at the pickup:

$$\begin{bmatrix} X \\ X' \end{bmatrix} = \begin{bmatrix} M + g \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} K \end{bmatrix} \begin{bmatrix} X_0 \\ X'_0 \end{bmatrix}$$

Inserting the correlator filter between the pickup and amplifier, the feedback kick becomes proportional to the difference between X_0 and the displacement one turn earlier:

$$\begin{bmatrix} X \\ X' \end{bmatrix} = \begin{bmatrix} M + g \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} (K - KM^{-1}) \end{bmatrix} \begin{bmatrix} X_0 \\ X'_0 \end{bmatrix}$$

One must choose the phase relation between pickup and kicker (i.e. adjust K) to optimize the damping term of the eigenvalue equation

$$\begin{bmatrix} X_0 \\ X'_0 \end{bmatrix} = \begin{bmatrix} I + gM^{-1} \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} K(I - M^{-1}) \end{bmatrix} \begin{bmatrix} X_0 \\ X'_0 \end{bmatrix}$$

Here I is the unit matrix. The last term on the left side, $(M^{-1})K(M^{-1})$, gives the action of the correlator filter. This added term is a special instance of a kicker with "memory" as treated by Khelifeto.⁵ With a horizontal tune of 2.4, the signal from a betatron oscillation is close to the maximum of the filter response, midway between nulls. Filter response falls off for lower fractional tunes, since the difference between subsequent turns becomes a smaller fraction of the full oscillation amplitude. The falloff is not precipitous; for a fractional tune of 0.25, the signal reduction is 3 dB. In some cases it should be possible to use a delay of two rotation periods in the filter to improve the response for low tunes. The output of the pickup electrode is a bipolar pulse, and the broadband amplifiers essentially reproduce this waveform. The pulse stretching of the amplifier and careful timing were sufficient to insure that the trailing "undershoot" of the beam signal should not antidamp the beam. Although the correlator filter did not attenuate the rotation harmonics by the 130 dB necessary to make any orbit error comparable to the electronics noise, the 1 mm orbit error in the position monitor was reduced to the equivalent of a 5 micron error. Active electronics could be used in series with the filter to get better results. Perhaps two correlator filters in series could be used; the output would then be

$$V(t) + V(t - 2T) - 2V(t - T)$$

This could be accommodated by changing the betatron phase advance between monitor and kicker, and the notch attenuations would multiply.

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Fig. 1. Schematic of correlator filter as part of betatron damper.

REF LEVEL /DIV
0.000dB 0.050dB
0.0deg 0.500deg

Fig. 2. Phase and amplitude inequality of T-1000

REF LEVEL /DIV
0.000dB 0.050dB
180.00deg 1.000deg

START 0.000Hz STOP 200 000 000.000Hz

Fig. 3. Phase and amplitude inequality of H-81-4 180° splitter.

REF LEVEL /DIV
0.000dB 0.050dB
-8.020deg 0.200deg

START 0.000Hz START 200 000 000.000 Hz

Fig. 4. Attenuation and phase shift of RG-58 cable relative to RG-318 cable. Propagation times of cables differ by 94.53 msec. The phase measurement is relative to this delay.

Fig. 5. Booster pickup signal input to correlator filter.

Fig. 6. Output from correlator filter.

Fig. 7. Response of betatron damper in booster to external excitation at 400 MeV. 2 msec per division.

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