LONGITUDINAL DAMPING IN THE TEVATRON COLLIDER

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Abstract

This paper describes the damper design for 6 proton on 6 pbar bunches in the Tevatron collider.[1] Signal pickup, transient phase detection, derivative networks, and phase correction via the high-level rf are covered. Each rf station is controlled by a slow feedback loop. In addition, global feedback loops control each set of four cavities, one set for protons and one set for antiprotons. Operational experience with these systems is discussed.

Introduction

Refer to Figure 1. Note that only the pbar circuits are shown, but another complete set exists for protons.

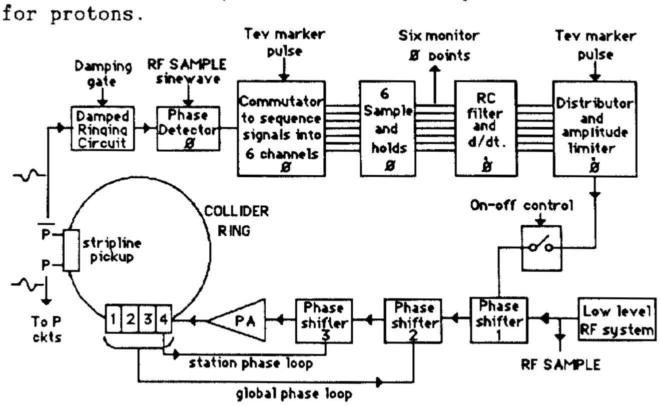

Figure 1: Collider longitudinal damper for 6×6 bunches. (Diagram shows pbar cavity loops and damping channels only.)

The damper chain consists of a beam pickup, a phase detector, a d/dt network to obtain $\dot{\phi}$, and a connection to phase shifter #1 of the high-level rf system.

The principle of the damper is described in Reference 2. The phase of the entire 4-cavity high level accelerating system is shifted slightly in response to a radial position error ΔR.

$$\Delta R = -\frac{R}{F_{rf}} \times \frac{1}{2\pi} \dot{\phi}_s \qquad (1)$$

where $\dot{\phi}s$ is the rate-of-change of bunch phase relative to low-level rf phase.

Whether the damper circuitry is run open or closed-loop, using the switch shown as "On-Off Control" in Fig. 1, monitor signals are available for all 12 bunches in the machine throughout injection, acceleration and storage. At injection, these signals allow one to readily minimize any systematic phase error between Main Ring bunches and collider buckets.

Pickup Location

Individual p and pbar bunches pass through the stripline directional pickup, which is 1 meter long and at room temperature but otherwise is like that described in References 3 and 4. Directionality of the pickup is ~33 dB - insufficient to totally discriminate between p and pbar bunches by directionality alone. We therefore placed the pickup at F17, distant from a collision point. The time separation between p and pbar bunches at F17 is 1.75 usec, adequate for complete isolation by time gating. There is, however, one short interval in machine operation when both p's and pbars pass through the pickup simultaneously - that is during collision - point cogging[5]. The damping loop should be off during this cogging.

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Ringing Circuit

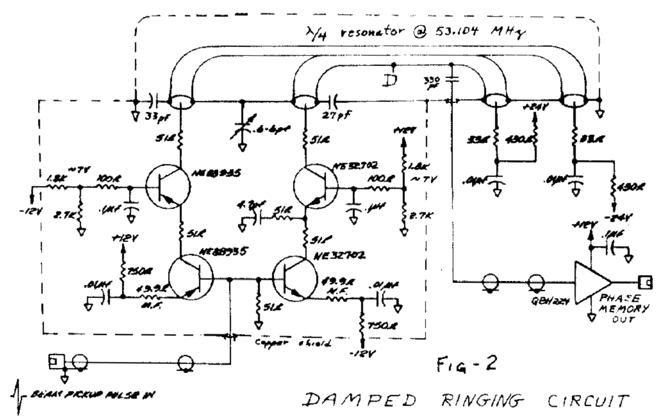

Fig-2 DAMPED RINGING CIRCUIT

Figure 2 is the arrangement to ballistically excite a λ/4 resonator with the bunch signal. To eliminate amplitude-dependent phase changes related to excitation of the sinusoid, the bipolar pulse from the pickup simultaneously feeds PNP and NPN transistors. At point D in Figure 2 there is connected a damping diode bridge to arrest the ringing before the next bunch arrives.

Phase Detector, Commutator and Sample-and-Holds

The phase detector, described in Reference 6, compares the phase of the bunch-excited ringing with the low-level rf sinewave. Phase detector output, an analogue signal of 1 volt/9°, is gated into a sample-and-hold channel for 150 nsec. Each channel is individually updated turn by turn. The Tev marker pulse insures that the phase signals are routed to the proper sample-and-hold channel.

$\dot{\phi}$ Signal, Distributor and Limiter

An active differentiator generates $\dot{\phi}$ from the ϕ signal, as in Reference 2. The $\dot{\phi}$ signals are successively gated into phase shifter #1. Gating times are set to cause a new phase change to arrive at the high level cavities just as the previous bunch leaves. Doing this gives the maximum available time for the cavity phase to readjust to the new value. The available time between bunches of 1 species is one-sixth of a turn or 3.5 microseconds.

Transiently, the phase shifter #1 may cover its full range, but a 375 nsec RC network limits the cavity excursion to ±3.42°. With this limiter setting, there is no danger of tripping an rf station. The ±3.42° δ phase shift corresponds to an individual bunch energy correction of Vpk sin δ eV, or ±72 KeV per turn maximum, given the typical ring voltage of 1.2 megavolts.

RF Station and Global Phase Loops

Each rf station[7] has its own slow phase feedback loop for phase tracking and noise reduction, providing ~20 dB improvement from dc to a few hundred Hertz. Cavity gap voltage is compared to the reference drive via a phase detector. The error signal drives phase shifter #3 to close the loop.

A fast global feedback loop controls each set of four cavities; one set for protons and one set for antiprotons. Each set of four cavities is driven independantly. The two rf sum signals are compared to their respective low level references by means of 150 nsec rise time phase detectors driving phase shifters #2. The proton and antiproton rf sum signals take into account all eight cavities in deriving proton and antiproton rf voltage. These fast loops correct phase for station trips and provide noise reduction in the operating system (maintaining collider luminosity). The loops have ~20 dB gain with dc - 10 kHz bandwidth.

Operational Experience

During the 1987 colliding beam run it was observed that coherent synchrotron oscillations would develop over a span of tens of minutes. The present 6x6 phase feedback systems was intended to rectify this.

At present the antiproton system is never turned on, and the proton system is active only during proton injection. The reason for this usage is explained.

Injection

One possible use of these phase feedback loops is to damp coherent synchrotron oscillations induced by either a phase or energy error between the Main Ring and the Tevatron rf systems at injection. Figure 3 contains a plot of the initial phase oscillation of a proton bunch. It turns out that the initial phase oscillation waveform is virtually identical when the 6x6 phase feedback is turned on. Figure 4 contains the phase oscillation waveform of a similar bunch as calculated by a computer simulation. Note that qualitatively the agreement between simulation and the Tevatron is rather remarkable.

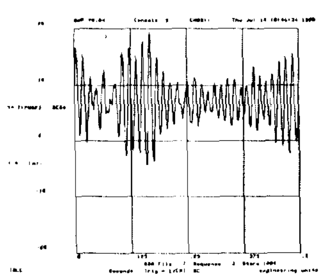

Figure 3: Synchrotron oscillation phase-proton bunch-Tevatron injection.

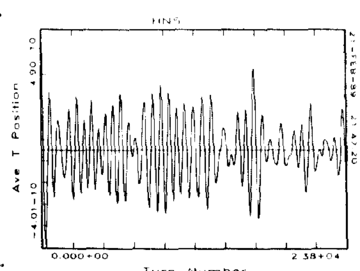

Figure 4: Simulation of synchrotron oscillation phase.

As will be shown later, the number of oscillations to damp to 1/e of the original amplitude is ~75. Figure 5 shows the phase space distribution of the computer sinulation test particles at 100 msec. intervals, which turns out to be about 40 synchrotron oscillations. Note that the large amplitude particles smear out into a uniform asimuthal density distribution far more quickly than the core particles, which even after 40 oscillations are lumped closely together. As it turns out, it is observed that turning on the proton 6x6 system at injection does not change the 95% interval within which the particles lie, but does slightly increase the core density of the bunch. Because of the very small B* at BO, this helps increase the luminosity of the store.

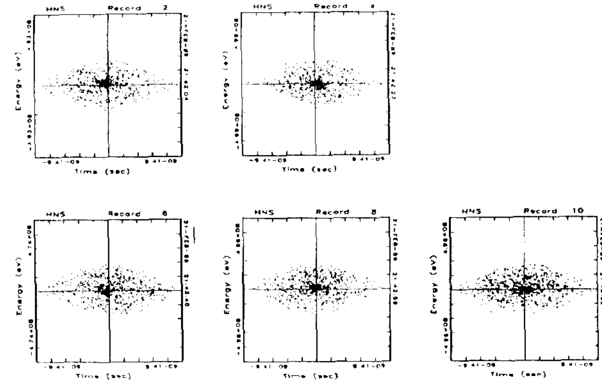

Figure 5: Simulation of longitudinal phase space, showing that large amplitude particles smear into uniform angular density distributions much faster than the core particles. Plots are spaced at 100 msec intervals.

Colliding and Single Beam Storage

The primary motivation for T:P6x6 and T:AP6x6 is to stabilize the synchrotron oscillation amplitude growth during long colliding beam stores. During the present collider run, this growth has only appeared during proton-only stores, and with a growth rate much smaller than that observed during the last collider run. During colliding beam stores, no synchrotron oscillation growth has been observed. As a result, these phase feedback loops are not used operationally during stores.

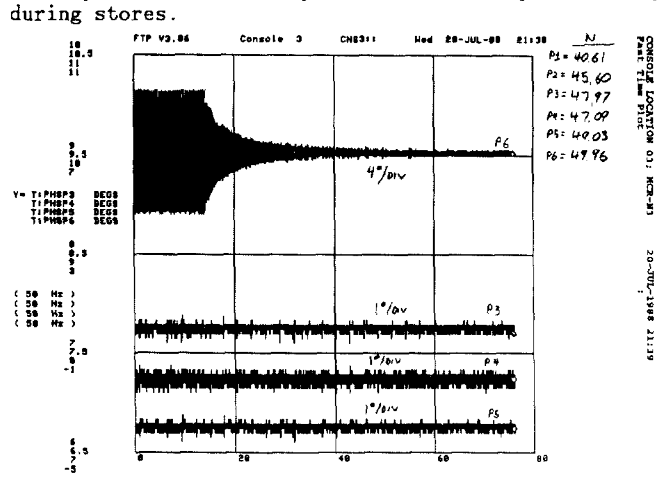

Figure 6: Phase oscillation amplitude vs time in a proton only store.

During proton only stores, it has been repeatedly observed that individual bunches will begin to exhibit coherent synchrotron oscillations with the loop off. This motion is measured using the 6X6 phase dectors. Figure 6 shows the phase motion of four bunches, labelled P3 through P6. Their intensities in units of 10^9 particles per bunch are listed on the left of the plot. Note that P6 has developed a very large steady state phase oscillation. At ~15 seconds into the plot, the T:P6x6 system was turned on. Note that the motion damped to 1/e of its original amplitude in about 2 seconds, which corresponds to the 75 synchrotron oscillations mentioned in the previous section. It has been noted that it was the most intense bunch that experienced coherent oscillation growth, and some effort has been made to calculate a longitudinal impedance from subsequent measurements. The result is as yet inconclusive.

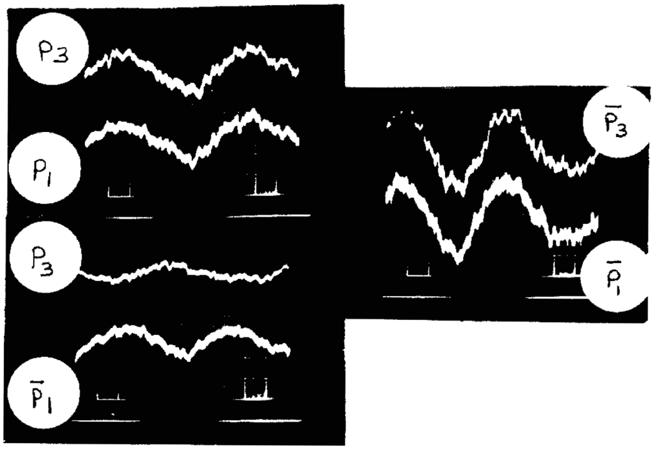

Figure 7: Phase vs time for both p and pbar.

Though growth in synchrotron oscillation amplitude has not been observed during colliding beam running, there is a steady state rms amplitude which can be measured. Figure 7 contains three photographs of such oscillations. In the top photograph the top trace is P3 and the bottom trace is P1. Note that the oscillations have the same amplitude and phase. In the right hand photograph, antiproton bunches A3 and A1 are similarly compared, again exhibiting identical amplitude and phase. In the botton photograph, proton bunch P3 is compared to antiproton bunch A1. In contrast to the upper two photographs, these bunches are not oscillating together in phase. This conclusion has been verified by looking at the cross coheerence of the two phase oscillations. Therefore, some global mechanism is affecting all protons identically, all antiprotons identically, but affecting protons differently from antiprotons. An obvious candidate mechanism is rf phase noise, since the proton and antiproton rf systems are independent. As yet no confirmation of this hypothesis has been forthcoming.

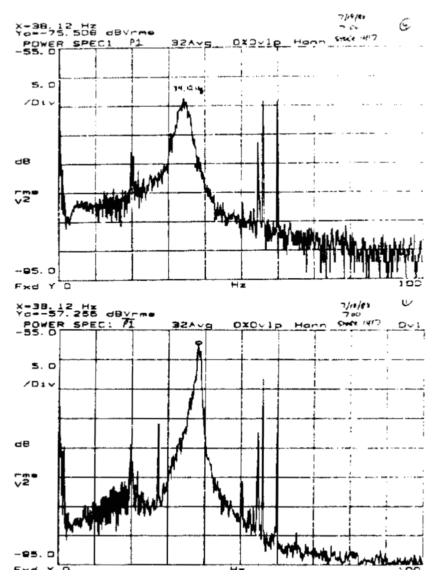

Figure 8: Fast Fourier transform of phase vs time data. Note that the proton and antiprotons have different oscillation frequencies and bandwidths.

Figure 8 contains the Fourier transform of the proton and antiproton motions. The bunch lengths of the proton bunches were longer than the antiproton bunches. Since the synchrotron frequency decreases quadratically with synchrotron amplitude, one would expect the average synchrotron frequency of the protons to be slightly lower and broader than the antiprotons, just as observed.

Since there exist coherent synchrotron motion, one would expect longitudinal emittance growth during a store. This is indeed the case, as demonstrated by the plot in Figure 9. The growth of these longitudinal emittances is not affected by T:P6x6.

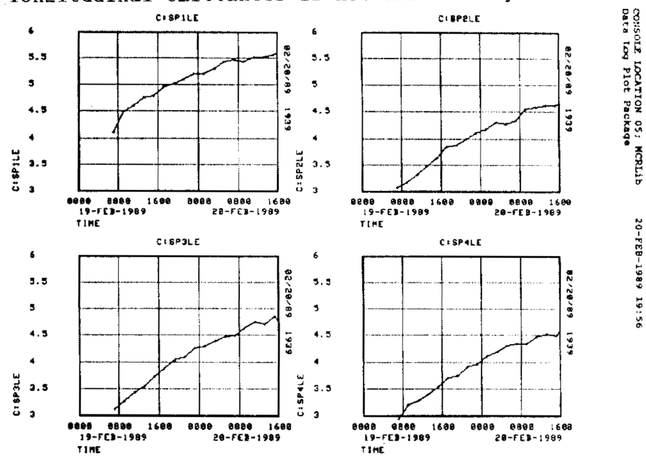

Figure 9: Longitudinal emittance vs time for proton bunches one through four.

Conclusions

Preliminary measurements of the affect of the 6x6 phase feedback systems in an operational setting have been made. Due to the disappearance of the motivating synchrotron oscillation growth measured in the last collider run, only the proton system is useful, and only at injection.

Further work is required to understand why coherent oscillations develop in proton only stores, but not when proton-antiproton collisions take place. In addition, the mechanism of the proton only oscillation growth should be identified and fixed.

Figure 1 shows that the next candidate for improvement is the low-level rf system, because at best the damping can only force the bunches to track the reference. Preliminary measurements indicate a potential improvement of 20 to 30 dB in lowering oscillator sideband noise in the 10 to 100 Hertz range which encompasses the synchroton frequency.

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