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SUPPRESSION OF TRANSVERSE INSTABILITIES BY FAST FEEDBACK IN THE FERMILAB BOOSTER

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Summary

Systems to damp radial and vertical instabilities of individual rf bunches in the Fermilab Booster are being implemented. The positions of individual bunches are derived from stripline pickups. The position information is transmitted over a variable delay, amplified, and applied to deflectors after one almost complete revolution, 6.25 horizontal and 6.75 vertical betatron wavelengths downstream of the pickup. Motivation, system concepts, design considerations, and initial operating experience are described here. Accompanying papers describe the electronics for signal processing and transmission.

Introduction

Systems to damp transverse beam instabilities on a bunch-by-bunch basis are being implemented for the Fermilab Booster proton synchrotron. The major purpose of the systems is to damp transverse betatron oscillations of the centroid of individual bunches, as can be caused by resistive-wall instabilities such as the head-tail-effect.[1] The intensity at which such instabilities appear depends on the distance to the walls of the vacuum chamber. Therefore, the system for the vertical coordinate was implemented first. It has been in use for a few months and initial operating experience will be described here. The radial system awaits the completion of its electronics, expected by June.

Design of the Systems

Booster Timing Considerations

The revolution frequency and the RF frequency of the Booster strongly influenced the design of the systems. The circumference C of the Booster is 474.4 meters. As the kinetic energy increases from 200 MeV to 8 GeV between injection and extraction, the velocity of the protons increases from .57 to .99c. Therefore, the revolution period T_{rev} decreases from 2.8 to 1.6 μsec. Since the deflectors are almost a full revolution downstream of the pickups, the position information must be stored for corresponding durations before application to the deflectors.

The radio frequency accelerating system of the Booster operates on the 84th harmonic of the revolution frequency, varying from 30 to 53 MHz as it forms and accelerates h = 84 bunches of protons. The spacing between bunches is then C/h = 5.56 meters, and the time interval between bunches, $T_{rev}/h = f_{rf}^{-1}$, varies from 33 to 19 nsec during the acceleration cycle. The need for the signal on the deflecting electrodes to change from one correction signal to the next in the interval between bunches thus led to an upper limit of a few nsec for rise and fall times and timing errors for the whole system. Although the time between bunches is longer early in the cycle, the bunch length is also longer (in fact the beam is initially unbunched), so that comparable timing requirements exist throughout the cycle after the beam is bunched.

Delay Concept

The requirements for a long and variable delay with simultaneous storage of position information for about 84 bunches led us to choose a cable-delay system with fast electronic switches to vary the delay. This concept is modeled after that of the Argonne ZGS damper system,[2] but the rf frequency is much higher in our case and the timing requirements correspondingly more stringent. Briefly, the delay works as follows. There are nine delay cables for each system (radial and vertical) whose electrical lengths[3] form a binary geometrical progression $T_m = 2^m\ T_o$, $0 \leq m \leq 8$. A binary logic system[4] digitizes the rf frequency, and the binary bits of the result determine which cables to switch into the delay path. The system is gated off for 3 μsec during the switching transients. Digitizing the rf frequency generates a binary number B proportional to the total required delay T_d, but because there are unavoidable fixed delays T_{fix} in the system, a subtraction is required so that the variable delay $T_{var} = T_d - T_{fix} = BT_o - T_{fix}$. The subtraction is simplified in these systems by adding a long cable so that $T_{fix} = 512\ T_o$. Then the subtraction is accomplished by merely ignoring the most significant bit of B. The fact that the frequency swing during acceleration is less than a factor of two makes this trick possible. The shortest cable length, T_o, is about 2.7 nsec (T_o=2.615 nsec radially, 2.730 nsec vertically) so that the variable delay switches its length about 450 times in 2.7 nsec steps during the 33 msec Booster acceleration cycle to cover the range from 2.8 to 1.6 μsec. The system is gated off a total of about 4% of the time during these switching intervals, mostly near the beginning of the cycle.

Functional Description

The design of the rest of the electronics was largely influenced by this choice of delay system. A functional block diagram of the vertical system is shown in Fig. 1; the radial system will be essentially identical. The proton beam passes through an enclosure containing 4 stripline pickups, two for each coordinate. The striplines are 50 Ω transmission lines, and each output is brought up from the tunnel on 50 Ω cables, through attenuators to balance the signals when the beam is on the desired orbit, to a fast position detector. The electronics for the system is described in detail in another paper submitted to this conference;[5] here only a brief outline of the electronics will be presented. The position error signal is decomposed into magnitude and polarity, and the two signals are transmitted[6] over the delay system using an amplitude modulation scheme on two different carrier frequencies. Finally the correction signal is applied through commercial RF power amplifiers (Instruments For Industry) to the deflection electrodes.

The power capability of about 100 Watts is such that a transverse momentum of about 10 keV/c can be generated per pass. With the gains currently in use, a position error of about one millimeter generates this maximum transverse momentum. Beyond this point the RF power amplifiers saturate.

The correction is applied at a place where the

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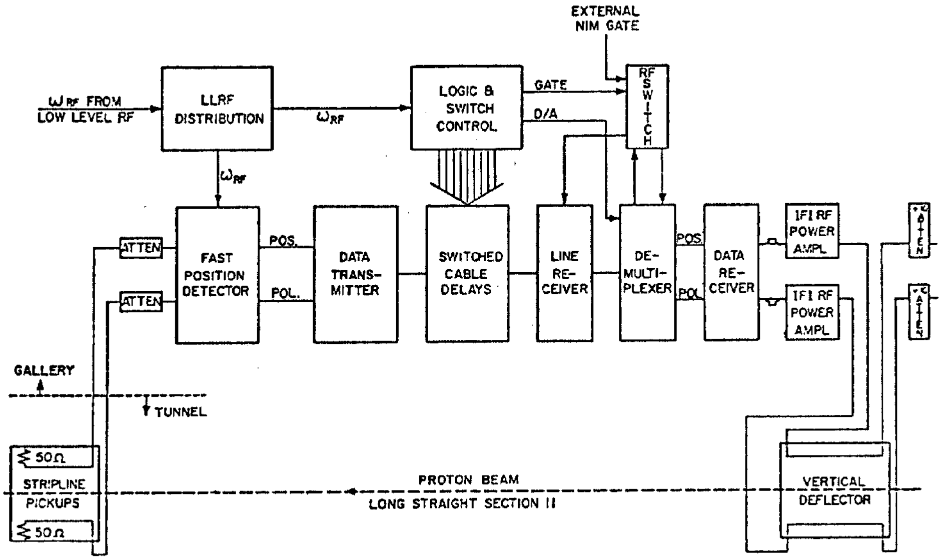

Fig. 1 Block diagram of the major functional components of the vertical superdamper.

detected position error has become an angle error, i.e. (2m+1)/4 betatron wavelengths downstream of the pickup. The vertical deflector is 6.75 λ downstream (the vertical tune ν_V is 6.8) and the horizontal deflector is 6.25 λ downstream (ν_H = 6.65). The pickups and vertical deflector are in Long Straight Section 11 and the hroizontal deflector is in Long 10.

Operational Experience

Initial Commissioning

In early tests of the vertical superdamper system, betatron oscillations induced by pinging the beam were observed to damp approximately exponentially, as shown in Fig.2, with a time constant of about 200 μsec, corresponding to about 100 turns, at a momentum of 1.5 GeV/c. This damping time agrees with that expected from the gain of the system, within the errors.

The system was also tested in the antidamping mode by merely interchanging the drive signals for the amplifiers feeding the two deflector plates. In this mode beam losses can be induced; it takes about 2 msec early in the cycle to destroy most of the beam. This is considerably longer than the damping time, probably because of the saturation of the rf power amplifiers for position errors greater than about a millimeter. The antidamping mode provides a sensitive way to determine the optimum fixed delay by means of a cable delay curve. In this way it was verified that the variable delay system correctly tracks the proton velocity. Another simple test of the system was the reduction in "fuzz" on the position error signal by almost an order of magnitude when the feedback loop was closed, as can be seen in Fig. 3.

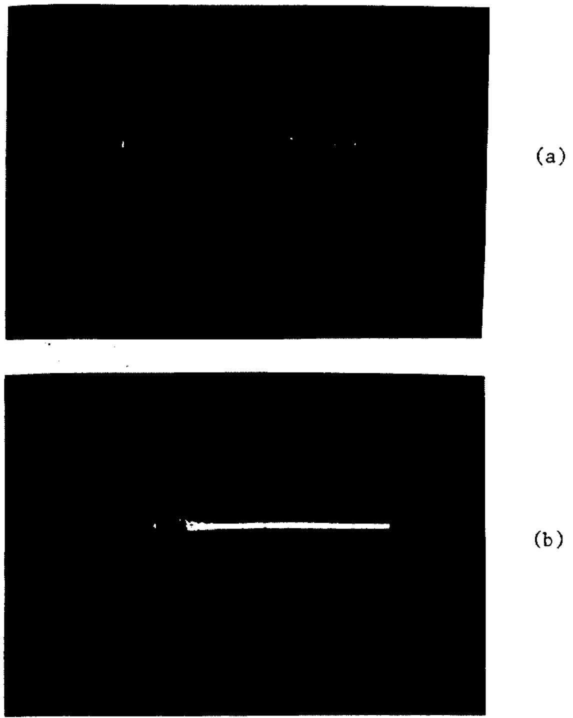

Fig.2 Coherent vertical betatron oscillations induced by a pulsed magnet with the superdamper (a) off, (b) on.

An unpleasant surprise in early operation was the sensitivity of the system's performance to the position of the beam at the pickups. It was subsequently realized that gating the system to zero during switching transients constitutes a beam kick unless the error signal happens to be zero before being gated off. In the vertical system this effect is not too serious and is currently controlled by means of balancing attenuators and a DC beam bump at the pickups. Radially more beam motion occurs, and a track-and-hold feature is being incorporated to furnish a slow moving average that can be switched to during switching transients.

Present Operation

The simplest theory of the head-tail-effect[1] provides a framework in terms of which our early operating experience with the vertical superdamper can at least be intelligently discussed if not always completely understood. The theory predicts a growth rate β for instabilities (in the absence of active damping) proportional to

$$\beta \propto \frac{d\nu}{dp}\left(\frac{1}{\gamma^2}-\frac{1}{\gamma_t^2}\right)^{-1}\left(1-4m^2\right)^{-1},$$

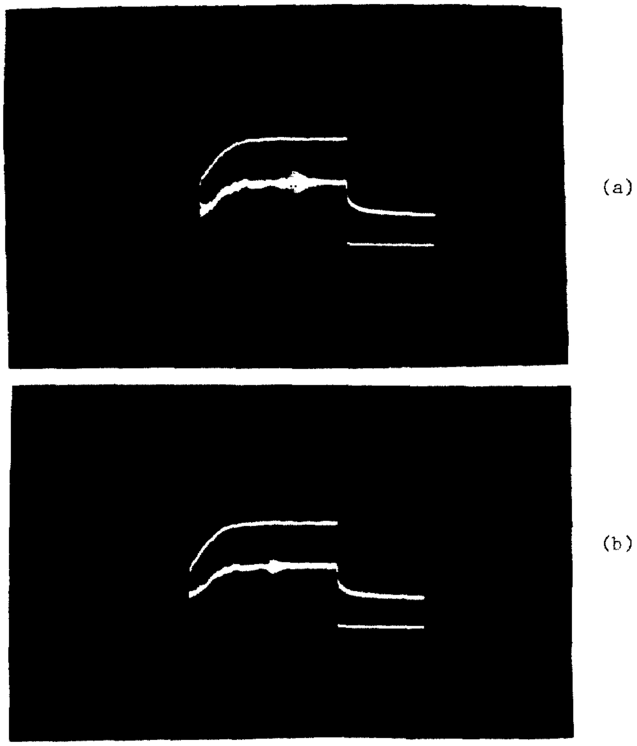

Fig. 3 The bottom trace in each photo is the position error signal; the top trace is the beam current with superdamper (a) off (b) on.

where $\frac{d\nu}{dp}$ is the chromaticity or rate of change of tune with momentum and m is the mode number of the bunch shape, $m = 0$ corresponding to motion of the bunch centroid. If β is negative the instability is damped. The theory then predicts that centroid motion ($m = 0$) will have the lowest threshold and that the chromaticity required for passive damping will change sign at the transition energy.

Before the vertical system was installed, head-tail effects were lessened by programmed sextupoles in straight sections. Best results were obtained when the sextupoles in the long straight sections, which primarily affect the vertical chromaticity, were ramped to give a nonzero chromaticity except when it changed sign near transition time, in agreement with the formalism outlined above.

With the active superdamper to control head-tail effects, the long straight sextupoles can now be ramped in order to zero the vertical chromaticity throughout the Booster cycle, leading to presumably larger good-field aperture. Some small gains in transmission have resulted from this mode of operation. In fact it is even possible to accelerate up to about 10^{12} protons per Booster cycle with the long straight sextupoles off, which causes opposite-sign chromaticities that strongly antidamp early in the cycle.

It was discovered empirically that transmission can be improved at high intensity by gating the vertical damper off for the first two msec of the cycle and for about five msec around transition time. Because of tune spread, coherent oscillations rapidly lead to emittance growth. It is believed that some emittance growth early in the cycle may be desirable in order to minimize space-charge tune shifts.

The explanation of the gate around transition time is more surprising. It was discovered that if the <u>vertical</u> damper is left on through transition, <u>radial</u> blowup ensues thereafter! Coherent bunch-by-bunch radial instabilities were directly observed (cf. Fig. 4) as well as larger radial beam size in the extraction line. If the damper is gated off, on the other hand, some vertical blowup occurs near transition time, and for some reason this prevents the more serious radial blowup. We thus look forward to the completion of the radial system to derive full benefit from the dampers. In the meantime optimal results are obtained with a radial position curve that results in a radial chromaticity that causes passive damping throughout the cycle. In particular this means a rapid radial motion through transition.

Fig. 4 The radial position signal shown here indicates bunch-by-bunch radial instabilities.

Acknowledgements

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