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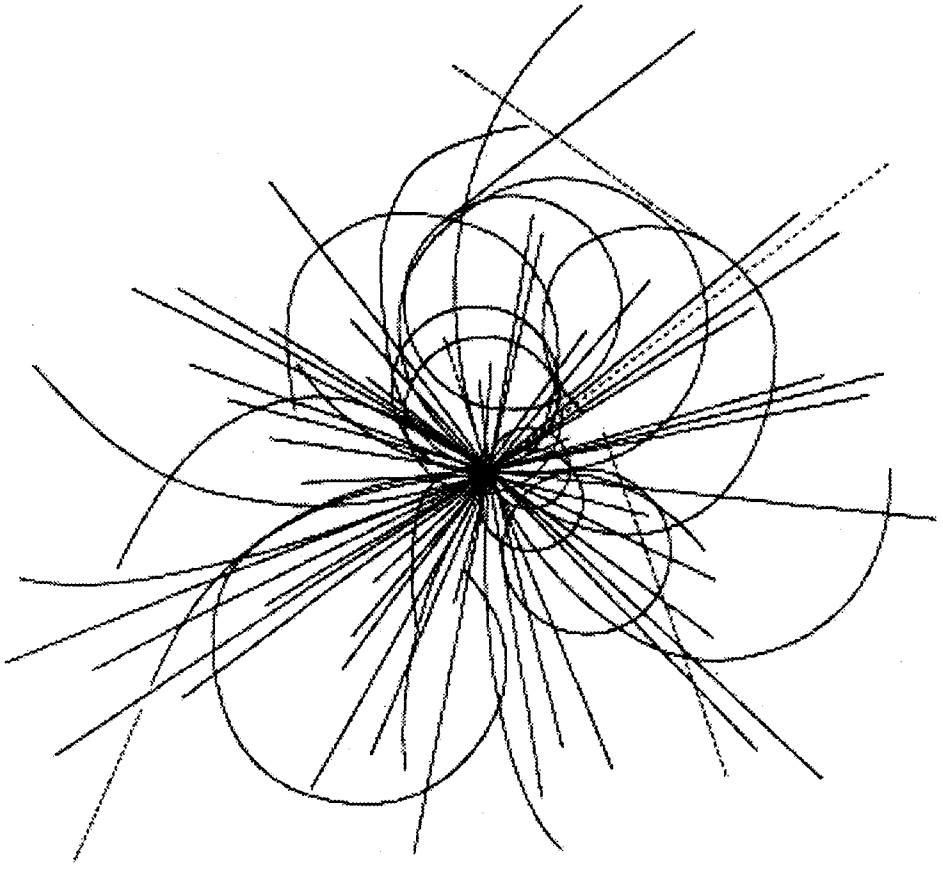

Superconducting Super Collider Laboratory

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The SSC Damper System*

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***Abstract*—A transverse beam damper system for providing stability against ground motion, resistive wall instabilities, and other effects in the Superconducting Super Collider (SSC) is outlined. Use of two monitors, as in existing designs, provides phase insensitivity. The novel feature is the use of two kickers, which permits almost exact orbit compensation within one turn. Bunch-by-bunch stabilization requires fast computation.**

I. INTRODUCTION

Transverse damping is very important for large circular accelerators, such as the Superconducting Super Collider (SSC) and the Large Hadron Collider (LHC), because of resistive wall instabilities, motion of quadrupoles due to ground motion, power supply ripple in dipoles, *etc.* A minimal transverse damping system consists of one Beam Position Monitor (BPM), followed downstream, with betatron phase advance that is an odd multiple of $\pi/2$, by one (probably electrostatic) kicker. For a beam bunch oscillating with optimal phase, this configuration can provide single turn, unity-gain damping. That is, the kicker can cancel the full betatron oscillation measured by the detector the first time the bunch passes the kicker. (We neglect throughout the possibility that the requested kicker angle exceeds its hardware limit.)

This minimal scheme has two disadvantages. One is the operational difficulty of preserving the required betatron phase relationship between pick-up and kicker as the lattice optics are altered. This is especially true because transit time requirements require the kicker to be displaced by a large fraction of the ring circumference. A well known fix for this problem is to provide two pick-ups, separated by roughly $\pi/2$ in phase.

The other problem with the minimal scheme is that the phase of the bunch is uncertain, and instead of full cancellation, damping of the betatron oscillation is provided only in some number of turns that depends on the lattice tune. Our proposed scheme, requiring the use of two kickers, spaced presumably by $\pi/2$, is able to cancel the oscillations for each bunch exactly, not just statistically. This cancellation is independent of the betatron oscillation phase. Damping of the transverse bunch oscillations may be treated as a pure trajectory task and, in a linear machine approximation, has an exact, single turn, solution, not just a statistical solution. Of course, the precision with which this can be accomplished depends on the accuracy of the beam position monitors.

Damping systems with two BPMs and two kickers have been discussed before [1-4], but without elimination of phase dependence. The presently proposed scheme will provide improved damping of instabilities with shorter growth times and noise sources of greater amplitude.

II. ANALYSIS

A simplified diagram of the proposed two-BPM, two-kicker scheme is shown in Fig. 1. As far as we know, the basic idea is original. It can be called "intelligent" in that it is assumed that a certain amount of calculation can be performed in the time available before the kicker voltage is applied.

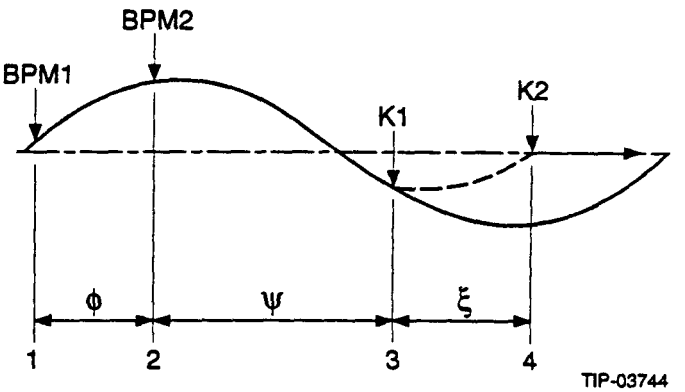

Fig. 1. Collider bunch-by-bunch transverse damping system. Kickers K1 and K2 apply kicks calculated from displacements X_1 and X_2, measured at BPM1 and BPM2. Betatron phase advances between elements, ϕ, ψ and ξ are defined as shown. The solid line is the uncorrected trajectory. The dashed line is the corrected trajectory.

We assume fully decoupled motion restricted to a single plane, say horizontal. Two beam position monitors, BPM1 and BPM2, separated by betatron phase angle ϕ, measure horizontal positions of the bunch in two locations along its orbit. This information is processed, and correction signals are sent to two kickers, K1 and K2, separated by approximately $\pi/2$. To simplify the picture, it will be assumed that the gain of the electronics is 1. At the first kicker, K1, an angular kick is produced which sets the slope of the bunch motion X' to some value, X_3', which is necessary to bring a bunch at the K2 position with zero displacement. Let us bring the bunch from point 3 to point 4.

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$$\begin{pmatrix} X_4 \\ X_4' \end{pmatrix} = \begin{pmatrix} \left(\frac{\beta_4}{\beta_3}\right)^{\frac{1}{2}} (\cos\xi + \alpha_3 \sin\xi) & (\beta_3\beta_4)^{\frac{1}{2}} \sin\xi \\ -\frac{1+\alpha_3\alpha_4}{(\beta_3\beta_4)^{\frac{1}{2}}} \sin\xi + \frac{\alpha_3-\alpha_4}{(\beta_3\beta_4)^{\frac{1}{2}}} \cos\xi & \left(\frac{\beta_3}{\beta_4}\right)^{\frac{1}{2}} (\cos\xi - \alpha_4 \sin\xi) \end{pmatrix} \begin{pmatrix} X_3 \\ X_3'(a) \end{pmatrix}$$

where $X_3'(a)$ is the slope of a bunch after the K1. Here α_i and β_i are the Courant-Snyder parameters of the lattice. Therefore,

$$X_4 = \left(\frac{\beta_4}{\beta_3}\right)^{\frac{1}{2}} (\cos\xi + \alpha_3 \sin\xi) X_3 + (\beta_3\beta_4)^{\frac{1}{2}} \sin\xi \; X_3'(a) .$$

Because we are seeking $X_4 = 0$, then

$$X_3'(a) = -\frac{1}{\beta_3}(\cot\xi + \alpha_3) X_3 ,$$

where

$$X_3 = \left(\frac{\beta_3}{\beta_2}\right)^{\frac{1}{2}} (\cos\psi + \alpha_2 \sin\psi) X_2 + (\beta_3\beta_2)^{\frac{1}{2}} \sin\psi X_2' ,$$

where

$$X_2' = \left(-\frac{1+\alpha_1\alpha_2}{(\beta_1\beta_2)^{\frac{1}{2}}} \sin\phi + \frac{\alpha_1-\alpha_2}{(\beta_1\beta_2)^{\frac{1}{2}}} \cos\phi\right) X_1 + \left(\frac{\beta_1}{\beta_2}\right)^{\frac{1}{2}} (\cos\phi - \alpha_2 \sin\phi) X_1' ,$$

where

$$X_1' = \frac{X_2}{\sin\phi\,(\beta_1\beta_2)^{\frac{1}{2}}} - \frac{X_1}{\beta_1}(\alpha_1 + \cot\phi) .$$

At the same time, the slope of the bunch before K1 $X_3'(b)$ is

$$X_3'(b) = \left(-\frac{1+\alpha_3\alpha_2}{(\beta_3\beta_2)^{\frac{1}{2}}} \sin\psi + \frac{\alpha_2-\alpha_3}{(\beta_3\beta_2)^{\frac{1}{2}}} \cos\psi\right) X_2 + \left(\frac{\beta_2}{\beta_3}\right)^{\frac{1}{2}} (\cos\psi - \alpha_3 \sin\psi) X_2' .$$

Therefore, the necessary kick $\Delta X_3'$ is

$$\Delta X_3' = X_3'(a) - X_3'(b) . \tag{1}$$

Again, from the matrix transformation,

$$X_4' = \left[-\frac{1+\alpha_3\alpha_4}{(\beta_3\beta_4)^{\frac{1}{2}}} \sin\xi + \frac{\alpha_3-\alpha_4}{(\beta_3\beta_4)^{\frac{1}{2}}} \cos\xi\right] X_3 + \left(\frac{\beta_3}{\beta_4}\right)^{\frac{1}{2}} (\cos\xi - \alpha_4 \sin\xi) X_3'(a) .$$

To bring the bunch slope to zero after K2, the necessary kick is

$$\Delta X_4' = -X_4' . \tag{2}$$

Eq. (2) can be simplified immediately if the optional choice, $\xi = \pi/2$, has been made. However, it is not essential for that condition to be satisfied exactly.

III. RESULT

The computations needed to determine kicks $\Delta X_3'$ and $\Delta X_4'$ can be expressed as two linear relations

$$\Delta X_3' = a_1 X_1 + a_2 X_2 \tag{3}$$

$$\Delta X_4' = b_1 X_1 + b_2 X_2 \tag{4}$$

where constants a_1, a_2, b_1 and b_2, are pre-calculated from the lattice constants. Since the phase differences ϕ, ψ and ξ are functions of the tune these constants must be recalculated when the lattice is retuned.

To insure that the information from BPM1 and BPM2 is maximally independent, which optimizes the accuracy of $\Delta X_3'$ and $\Delta X_4'$, their phase separation should approximately satisfy the condition $\phi \cong \pi/2$. Furthermore, to reduce degradation resulting from the possible amplification of stochastic excitations occurring between pick-up locations, the option of increasing their separation by an integer multiple of π has to be declined. However, in the case of using more than two pick-ups they could be separated by the distance of up to one third of the ring, and signals should be sent backward to the kicker system.

IV. COMMENTS

In any practical system, since the bunch will outrun any correction signal to downstream kickers, one must wait for almost one revolution of the bunch around the collider circumference. This sets a natural limit on the performance of the damping system. All stochastic deviations accumulating in one turn can then be corrected after an additional turn. A half-turn or even a quarter-turn scheme is feasible if the correction signals could be sent across the ring fast, presumably via the air. Redundant high speed links should be installed for this.

The configuration can be used for bunch-by-bunch damping. If digital arithmetic is used, analog-to-digital conversion of bunch displacements must occur at the 60-MHz bunch passage frequency, and performing the calculations of Eqs. (3) and (4) must proceed at a 240-Megaflop rate. Also the kicker risetime must correspond to the same 60-MHz frequency. It appears to be technically possible to meet these requirements. Even if not, the system could be used to damp all but the highest frequency multibunch modes.

A variant of the proposed scheme would permit exact cancellation of oscillation using the single kicker, which would effectively play the role of both K1 and K2. On a first passage a kick is applied that causes the bunch to be centered when it next passes, at which time the unwanted oscillation is cancelled. This scheme requires two turns to cancel the oscillation. This might be expected to allow stochastic beam degradation to be greater by a factor equivalent to raising the noise amplitude by $\sqrt{2}$. More serious is the fact that, for unfavorable betatron tunes (close to integer or half integer) the kick on first passage has to be large to achieve zero displacement after one turn. In that case two kicks "fight" each other, with the second kick largely undoing the effect of the first kick.

The damping action of a traditional, single-kicker, damper occurs over a few revolution periods, with the actual number depending on tune. On any one passage only the "correct phase" component can be cancelled, and the "wrong phase" component is unaffected. On the next passage, what was previously the wrong phase component has been phase shifted so that an appreciable fraction is cancelled. Again, assuming stochasticity causes square-root dependence, the improvement coming from going to the proposed two-kicker scheme approaches a factor of two reduction in noise amplitude.

The damping system proposed could be used for all stages of collider ring operation – injection, acceleration, collision – if the dynamic range of the apparatus is made wide enough, from micrometers to millimeters. But probably rf power considerations will force the existence of a separate injection damper.

A potential weakness of any damper system is that noise on the BPM signals will cause emittance growth. If the noise level is too great, the damper will do more harm than good. The proposed intelligent damper system does, however, permit a variable trade-off between frequency response and noise filtering. By performing a running average of pick-up coordinates (appropriately corrected for a time dependence) over the neighboring N bunches, high frequency noise can be reduced by $\sqrt{N}$. However, this will limit the stabilization to instability wavelengths of the order of N bunches, roughly speaking. Presumably, this mechanism will work fine for all combined "slow" beam disturbances, due to ground motion, power supply ripples, *etc.*

V. ACKNOWLEDGEMENTS

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