A Damper to Suppress Low Frequency Transverse Instabilites in the VLHC

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Introduction

The 1996 Snowmass summer study highlighted the lowest frequency transverse coupled bunch instability as an important consideration for the design of a low field (<2 T) VLHC (Very Large Hadron Collider).[1] The growth rate was estimated to be 1/3 of the revolution period. This instability is routinely suppressed with electronic feedback[2] at operating machines such as the Main Ring and Tevatron, but was thought to be "beyond the state of the art"[3] for the VLHC–presumably because the calculated growth time was shorter than the revolution period. The purpose of this paper is to describe a feedback system (a "damper") using straight-forward techniques on a very modest scale that would suppress the instability.

Should We Believe the Growth Rate Estimate?

The growth rate is calculated assuming that thecollective motion is the same as the single particle motion plus a perturbation. The effect of the perturbation is evaluated by averaging over the motion. It seems that this procedure can hardly be valid when the instability grows by e^3 in a single turn. Nevertheless, it is plausible that the answer is at least roughly correct: one can observe similar growth rates (of the order of 1000 $\sec^{-1}$) in the Tevatron and other FNAL machines. These growth rates only seem short when compared to the very long revolution period of the VLHC. For the purposes of this paper, I will assume that we are required to achieve a damping time of 1/3 of a revolution period

The Issue

The main issue is whether the resistive wall instability dictates the aperture required. The resistive wall impedance depends on the pipe radius (b) and mode frequency (f) as follows:

$$Z_{\perp} \propto \frac{1}{b^3\sqrt{f}}.$$

The impedance can be drastically reduced by increasing the beam pipe aperture. However, the cost of increasing the aperture is significant and it would be desirable to have the aperture as small as possible.

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[1] G. Dugan, P. Limon, and M. Syphers, "Really Large Hadron Collider Working Group Summary," *New Directions for High-Energy Physics, Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics, Snowmass '96*. This document is available from Stanford Linear Accelerator Center's World Wide Web side, http://www.slac.stanford.edu/a.

[2] The dependence of the growth rate on the chromaticity can be and is also used to control the instability.

[3] J. Rogers, "Collective Effects and Impedances in the RLHC(s)," *New Directions for High-Energy Physics, Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics, Snowmass '96*. This document is available from Stanford Linear Accelerator Center's World Wide Web side, http://www.slac.stanford.edu/a.

What Bandwidth is Required?

The growth time is assumed to be about 1 msec for the lowest mode. Higher order modes will be unstable with growth rates proportional to $f^{-1/2}$ and will be Landau damped when the growth rate is comparable to the synchrotron frequency (~1 Hz). Assuming 100 Hz for the lowest unstable line, lines are unstable up to 100 MHz (this is almost all the lines). Let us consider only the fastest growing modes (those below 100 kHz) and leave the others to a "conventional" bunch-by-bunch damper with a single turn delay.

System Concept

A signal is derived from a "difference" pickup, *i.e.*, a pickup that is sensitive to the product of the beam current and its transverse position. The signal is amplified and transmitted downstream to a point 90° advanced in betatron phase. The signal is further amplified and applied to a kicker to provide the negative feedback required to stabilize the beam. The fact that the signal arrives late and is applied to succeeding bunches doesn't matter at these low frequencies (because the phase error is small).

Pickup

I assume that a capacitive pickup is used to derive a signal proportional to the beam intensity times displacement. The pickup is made of two striplines terminated by an open circuit at one end and a high impedance amplifier at the other. The signal voltage is given by:

$$V_p = S\, i_b\, Z_0 \frac{2\Delta x}{g}$$

With a beam current (i_b)=4 A, a characteristic impedance (Z_0)=50 Ω, an electrode gap (g)=3cm, a sensitivity factor (S)=0.8, and a displacement (Δx)=0.1 mm, one obtains V_p=1 V.

Kicker

I assume we want to kick a reasonable fraction of the 0.1 mm displacement at the kicker. A displacement of Δx at the pickup is equivalent to an angular displacement at the kicker of

$$\theta_k = \frac{\Delta x}{\sqrt{\beta_p \beta_k}} = 231 \text{ nrad}$$

when $\Delta x = 0.1$ mm, $\beta_p = 250$ m,

and $\beta_k = 750$ m.

A stripline kicker will provide a deflection of

$$\Delta\theta = 2\sqrt{2}\,\frac{SV\bullet}{gE}$$

$$V = \sqrt{PZ_0}$$

For a sensitivity factor (S)=0.8, length (●)=10 m, electrode gap(g)=3 cm, final amplifier power (P)=2000 W, characteristic impedance (Z_0)=50 Ω, and E=3 TeV one finds $\Delta\theta$=80 nrad. I consider this to be an adequate kick, but a larger kick could be obtained by using a longer kicker or by making a magnetic (ferrite loaded) kicker. Both options decrease the system bandwidth, but it is only a practical concern for a slow rise-time magnet kicker. The 10 m long kicker does not need to be a continous object: For example, ten 1-m long kickers connected in series would provide the same function.

System Gain

The critical feature of the damper is the gain. We require a damping time of 1/3 of a turn or a damping rate of about 3. A total of 10 systems distributed around the ring, each with a damping rate of 1/3 would provide the necesary feedback. With the pickup and kicker structures described previously, an electronic gain of about 300 (50 dB) is required.

Beam Heating Rate

The beam heating rate resulting from a broadband noise spectrum is:

$$\begin{aligned}\frac{d\varepsilon}{dt} &= 24\pi\beta_k f_0 \frac{Z_0 S^2 \bullet^2 P}{g^2 (E/e)} \\ &= 24\pi \bullet 750 \bullet 464 \frac{50 \bullet 0.8^2 \bullet 10^2 P}{0.03^2 \bullet \left(3\times 10^{12}\right)^2} \\ &= 6.6\times 10^{-14}\,\pi P \text{ m - rad/(W - sec)}\end{aligned}$$

where I have chosen to evaluate the heating at the injection energy of 3 TeV. Converting to normalized emittance and somewhat more convenient units

$$\frac{d\varepsilon}{dt} = 0.76\pi \text{ mm - mrad}/(\text{W - hr})$$

The maximum total damper power level that could be tolerated appears to be in the range of 0.1 to 1 W. Ten damper units running at a full power of 2000 W would result in excessive emittance growth, but a $5\ \text{nV}/\sqrt{\text{Hz}}$ preamp at this gain (300) and bandwith (1 MHz) generates less that 1 μW–well below the maximum tolerable level. Most of the amplifier power is required to handle beam transients and offsets that do not cause emittance growth.

System Power

The required damping rate determines the system gain. In an ideal system no power is required because the beam is not oscillating. A practical system requires power to amplify the undesired signals at the input of the amplifier. These signals could include:

Static closed orbit distortion caused by steering errors.
Dynamic closed orbit distortion caused by power supply ripple and ground motion.
Turn by turn oscillations following injection.
Amplifier Thermal Noise.

These extraneous signals affect the damping only if they reduce the system gain by saturating the feedback amplifier. With a unit power amplifier of 2000 W and a gain of 300, the maximum effective orbit offset that can be tolerated about 0.1 mm. The closed orbit distortion can be suppressed by a factor of 10 (probably more in a slow cycling machine like the VLHC) by electronically nulling the damping pickup. Thus, the tolerance on the closed orbit at the damper pickup is the fairly comfortable value of 1 mm. If necessary, real-time feedback from the damper pickup to the orbit correction system could be used.

The analysis of power supply ripple and ground motion is well beyond the scope of this note, but it seems reasonable to assume that it is much less than the 1 mm closed orbit error. The electronic pickup nulling circuit will be effective for nulling low frequency motion (such as ground motion and motion at the synchrotron frequency), but probably not be effective for power supply ripple at multiples of 60 Hz.

A maximum injection oscillation of 0.1 mm could be tolerated by the damper system with no degradation in performance (neglecting any closed orbit error). I don't know whether this tolerance will be difficult to achieve, but it is clear that it must be achieved to obtain a beam size of 10π mm-mrad (the rms beam size of a 10π mm-mrad at β=250 m is 0.36 mm). Even if the emittance requirement is relaxed somewhat, the damper system still has some margin assuming that the beam is injected in short batches. Only the most recently batch will saturate the amplifier: the damper will still work as long as the batch length is short compared to the distance required for the instability to grow by a power of *e*.

It is important to note that the damper system power that comes from the motion of the beam does not normally result in emittance growth. In fact, the system will have the beneficial effect of reducing emittance growth from these other noise sources. The amount of reduction depends on the ratio of feedback system gain (damping in 1/3 of a turn) to the decoherence time of the beam, which depends on the spread in synchrotron and betatron tunes. The decoherence time has not been estimated, but it seems likely that it would be considerably greater than one turn.

Bandwidth

The main limitation of the bandwidth of the system described above is the transit time delay between pickup and kicker. The pickup to kicker distance must be about 1000 m to get 90° phase advance between pickup and kicker. The signal could be transmitted with "foam" coaxial cable, which has a beta greater than 0.8. The difference in delay between the beam and the signal is therefore about 200 m at the speed of light plus an estimated electronics delay of 50 nsec or about 700 nsec total. The maximum frequency consistent with this delay is about 1/8 ∞ (1/700 nsec) = 179 kHz. This bandwidth meets the requirements for this system (100 KHz), but it could be extended by using an air-dielectric type cable.

Concluding Remarks

It appears to be straight-forward to damp low frequency instabilties in the VLHC. The system described damps any type of transverse, dipole, coupled bunch instability provided that the bunch-to-bunch phase advance is small enough to be included in the system bandwidth. Single bunch instabilities, such as transverse mode coupling instabilities, and high-frequency coupled bunch modes would not be damped by this type of system.

The system is not particularly challenging in any respect. It is fairly easy to provide stronger feedback if necessary by increasing the gain (more systems, more power, more electronic gain, stronger kickers, more bandwidth, etc.). The technique is not speculative and should not be controversial. A similar system was used to damp the resistive wall instability in the Main Ring (but only the lowest band). The parameters of the proposed system (power, gain, etc.) are similar to or simpler than systems already in use.