INITIAL RESULTS OF SIMULATION OF A DAMPING SYSTEM FOR ELECTRON CLOUD-DRIVEN INSTABILITIES IN THE CERN SPS

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Abstract

Single and multi-bunch instabilities on bunch trains driven by electron clouds have been observed in the CERN SPS for some years. In this paper, we present initial results to implement a damping system in a computer simulation of a single bunch vertical instability using the HEADTAIL code. The code simulates the interaction between a proton bunch and a uniform electron cloud that has built up inside of the beam pipe. The feedback is implemented as a corrective kick calculated from the vertical centroid of each slice of the proton bunch with a one turn delay. The bandwidth of the feedback is varied by filtering the slice information along the bunch. Initial results indicate that the instability can be damped with a minimum bandwidth of 300 MHz with a relatively high gain.

INTRODUCTION

In high current proton beams, as accelerated in the SPS, an electron cloud can accumulate in the vacuum chamber. The electron cloud is generated by proton beam induced multipacting initiated by the presence of electrons generated by photoemission or ionization of residual gas. Sufficiently dense electron clouds can lead to beam instabilities in both transverse planes. In dipole magnets these electrons are confined to move in helices in the vertical plane, leading to strong instabilities in this plane. In the SPS, both single and multi-bunch instabilities have been previously observed, particularly in dipole magnets. The results of the simulation code HEADTAIL [1], a program created to study single bunch electron cloud effects, suggest that single bunch electron cloud effects in the SPS are significant only in dipole magnets. This electron cloud related instability can cause significant emittance growth and beam blowup. A summary of observations in the CERN SPS accelerator can be found in [2]. In this paper, we discuss the development of an extension to the HEADTAIL code that simulates a simple single bunch feedback system. This is used to determine the minimum bandwidth and gain required to damp the instability.

HEADTAIL SIMULATION RESULTS

The HEADTAIL algorithm tracks a single bunch by slicing it up into a number of equally spaced slices and tracking the transverse position of each slice at a number of interaction points. As we only expect large electron cloud effects to occur in dipole magnets in the SPS, all ten interaction points are chosen to include only dipole fields. A measure of the transverse oscillation of each slice is given by the "action" weighted by the number of particles in that slice. This quantity is defined as

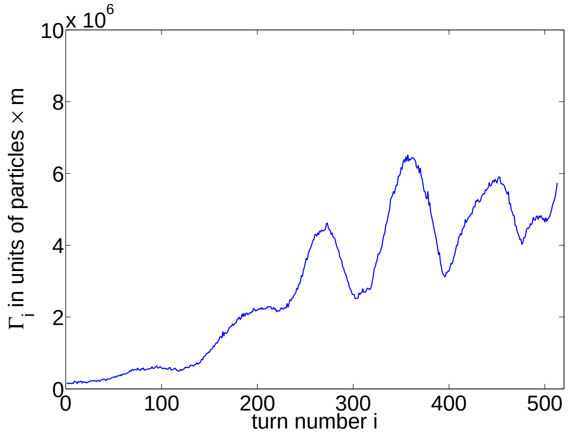

Figure 1: Γ vs. turn number with no feedback for 55 GeV/c.

$$Y_{i,j} \equiv N_{i,j}\sqrt{y_{i,j}^2 + \beta_y^2 {y'_{i,j}}^2} \tag{1}$$

where i is the turn index, j is the slice index, y is the vertical centroid position, y' is the angle of the trajectory of each slice, and $\alpha = 0$ at the interaction points. Examining the growth of the maximum of Y for a bunch over time provides a convenient way to measure the growth of the instability. Therefore, we will typically plot the quantity

$$\Gamma_i \equiv \max\left[Y_{i,j}\right] \tag{2}$$

In Fig. 1 we plot Γ_i vs. turn number for 55 GeV/c and the beam parameters listed in table 1. 55 GeV/c has been identified as one of the future injection energies of the SPS with the PS2 accelerator [4] and represented therefore one of the energies we have concentrated the study on [3]. In general, we observe a very asymmetric behavior; the tail of the bunch has a large amplitude while the head of the bunch does not oscillate, see Fig. 2. As there is a dipole moment present it is worth to test first whether a feedback on this dipole moment alone can cure the instability or whether a higher bandwidth is required that can resolve the motion within the bunch.

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Table 1: Bunch parameters for the simulation at 55 GeV/c momentum [3].

Vertical Beam Size (mm)	1.95
RMS Bunch Length (m)	0.217
Long. Momentum Spread (1σ)	0.0008
β_y (m)	72
Horizontal Tune	0.13
Vertical Tune	0.185
Synchrotron Tune	0.003

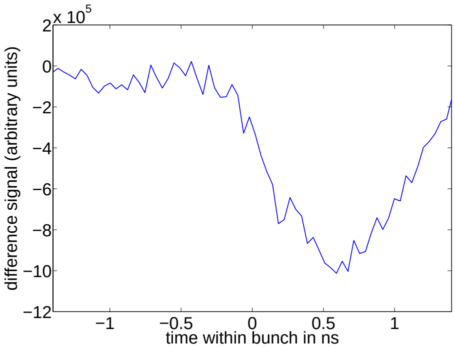

Figure 2: A typical difference signal vs. bunch length plot for 55GeV/c (turn 150)

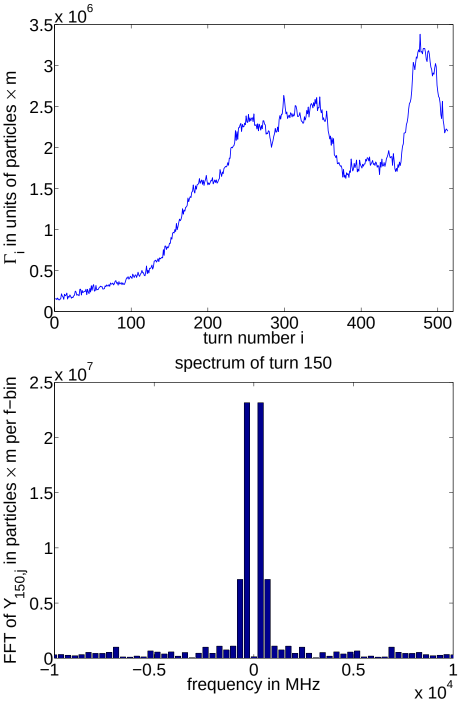

Figure 3: Γ vs. turn number with simple dipole feedback and FFT of turn 150 for a gain factor of 1/5 and spectrum.

DIPOLE FEEDBACK MODULE

In order to check if feeding back on the dipole motion of the bunch is sufficient or not to cure the instability we have developed a simple dipole feedback module for the HEADTAIL code. The HEADTAIL algorithm tracks the transverse position of each slice at ten "interaction points" along the ring. Each of these interaction points is assumed to have identical twiss parameters and $\alpha = 0$. At each interaction point, the dipole feedback algorithm calculates the vertical average offset of the bunch using the vertical centroid slice positions according to

$$y_{\mathrm{dipole}} = \frac{\sum_j N_j y_j}{\sum_j N_j} \qquad (3)$$

where y_j is the position of the j_{th} slice and N_j is the number of particles in the j_{th} slice. The quantity $g \times y_{\mathrm{dipole}}$ is then subtracted from the current vertical position of each macroparticle in every slice, where $g \leq 1$ is the normalized gain. It is important to note that the dipole feedback module gives an instantaneous position correction. That is, a dipole correction is subtracted from the current position of each particle immediately after each interaction point. While such a feedback is unphysical (i.e. one cannot correct a position instantaneously) it represents a best case scenario; if feeding back on dipole motion will not work using this type of simple feedback, it will not work for any more complicated method.

In Fig. 3 we show the results of dipole feedback for a large gain. The top plot shows Γ vs. turn number and the bottom plot the Fast Fourier Transform of turn 150 (a typical case). While the growth rate of the instability is somewhat smaller than the growth rate without feedback, the instability has by no means been damped. In the spectrum it is visible that the low frequency (DC) has been suppressed, but higher frequencies persist practically unchanged [3]. This indicates that while feeding back on the dipole removes the dipole component of the bunch difference signal, it is not sufficient to damp higher modes and therefore does not cure the instability. In particular, this type of feedback will not damp modes that have odd symmetry around the bunch center because they have zero dipole component. Therefore, in order to have any chance of damping the instability we must implement a feedback with a wide enough bandwidth to damp both even and odd modes.

VARIABLE BANDWIDTH FEEDBACK MODULE

A variable bandwidth feedback module was developed [3] which also uses a more physical method to generate the feedback signal; namely we give each macro particle in the bunch a kick once per turn rather than changing its position once per interaction point. Both the "pickup" and "kicker" are located at the same point in the ring, at one of the interaction points of the simulation with $\alpha = 0$. The required kick signal can be calculated using the difference signal of each slice at the current and previous turns

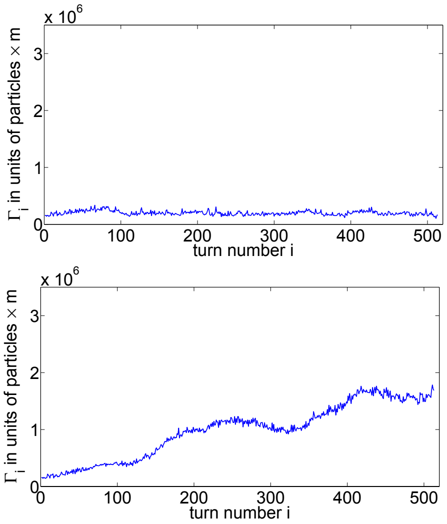

Figure 4: Γ vs. turn number with 300 MHz bandwidth limit with $g = 40$ (top) and 200 MHz (bottom) with large gain.

according to the following formula [5]

$$\Delta y'_{i,j} = \frac{g}{\sum_j N_j}\left[\frac{N_j y_{i,j}}{\beta_y \tan(2\pi q_y)} - \frac{N_j y_{i-1,j}}{\beta_y \sin(2\pi q_y)}\right] \quad (4)$$

where $y_{i,j}$ is the position of the j_{th} slice after the i_{th} turn, q_y is the fractional vertical machine tune, β_y is the vertical beta function at the position of the feedback system and g is a gain factor. In order to limit the bandwidth of the kick signal,$\Delta y'_{i,j}$, we filter the signal before "kicking" the bunch. A way of doing this is to implement a moving average filter with adjustbale weight functions. The feedback module has been coded so that it is relatively easy to modify the weighting function and therefore easy to vary the bandwidth of the feedback system. We ran a simulation with bandwidth limited feedback limited to 500 MHz, 400 MHz, 300 MHz, and 200 MHz. In all of these simulations, the kick signal was filtered using a windowed sinc filtering function [3]. Fig. 4 shows Γ vs. turn number for two different bandwidths. The results show that the minimum bandwidth needed to damp the instability is around 300 MHz.

NORMALIZED GAIN

All of the gain factors quoted so far have been unnormalized. Typically a normalized gain is defined such that a single kick with a gain of one will fully correct the current y' assuming linear betatron motion. Hence,

$$\Delta y'_{i,j} = g_{\text{norm}} y'_{i,j} \quad (5)$$

Assuming $\alpha = 0$ at the pickup and purely linear betatron motion one can show that

$$y'_{i,j} = \frac{y_{i,j}}{\beta_y \tan(2\pi q_y)} - \frac{y_{i-1,j}}{\beta_y \sin(2\pi q_y)} \quad (6)$$

Table 2: List of the minimum gain factor and normalized gain required to cure the instability using feedback with different bandwidths.

Minimum Gains for Various Bandwidths		
Bandwidth	Gain Factor	Normalized Gain
500 MHz	10	0.16
400 MHz	20	0.32
300 MHz	40	0.64

Therefore, examining Eq. (4), we determine that

$$g_{\text{norm}} \equiv \frac{g N_{i,j}}{\sum_j N_{i,j}} \quad (7)$$

Hence, the normalized gain effectively changes over the bunch length. In a real feedback system it is possible to vary the gain over the bunch length. Therefore, a useful quantity to quote is the maximum normalized gain for each turn. But in doing this we do not take into account the asymmetric shape of the difference signal that we are trying to damp. A more appropriate quantity to quote is the normalized gain for the slice that has the maximum difference signal. This represents the actual minimum gain required to damp the instability. In Table 2 we show the normalized gain for the different bandwidth limiting cases that we have looked at [3].

CONCLUSION

Using an extension to the HEADTAIL simulation code we have shown that the electron cloud driven vertical instability in the SPS cannot be cured by dipole feedback alone. A minimum bandwidth of 300 MHz is necessary to resolve the motion within the bunch and successfully suppress the oscillations.

ACKNOWLEDGMENTS

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