SIMULATION OF A FEEDBACK SYSTEM FOR THE ATTENUATION OF e-CLOUD DRIVEN INSTABILITY*

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Abstract

Electron clouds impose limitations on current accelerators that may be more severe for future machines, unless adequate measures of mitigation are taken. Recently, it has been proposed to use feedback systems operating at high frequency (in the GHz range) to damp single-bunch transverse coherent oscillations that may otherwise be amplified during the interaction of the beam with ambient electron clouds. We have used the simulation package WARP-POSINST and the code Headtail to study the growth rate and frequency patterns in space-time of the electron cloud driven beam breakup instability in the CERN SPS accelerator with, or without, an idealized feedback model for damping the instability.

INTRODUCTION

Various methods are being employed to prevent the buildup of electron clouds in particle beam accelerators to reach critical densities above which they can affect the beam quality, such as surface scrubbing, coating, grooving, etc. [1] However, these methods may be time consuming and expensive, and it is unclear if they can be sufficient for all the configurations that are in plan for the near-future. It has been proposed recently [2] as a complement to the abovementioned techniques for buildup reduction (or eventually a replacement), to mitigate the effect of electron clouds on the bunches by using feedback systems. In this paper, we investigate using computer simulations, electron cloud buildup in the SPS, its effect on one bunch at the tail of a batch, and its mitigation using idealized feedback models, considering the parameters given in table 1 for an intermediate beam energy of 120GeV.

SIMULATION OF ELECTRON CLOUD BUILDUP

We have used the code POSINST [3, 4] to simulate the buildup of an electron cloud in one dipole section of the SPS, with the parameters given in table 1. The secondary electron yield was varied between 1.1 and 1.3, leading to a maximum average electron density ranging between $1 \times 10^{10} m^{-3}$ and $5 \times 10^{11} m^{-3}$. These values were obtained averaging the electron density over the whole chamber (rectangular $7.7cm \times 2.25cm$). However, the electron cloud distribution occupied only a fraction of the chamber,

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Table 1: Parameters used for simulations of e-cloud effects study in the SPS

beam energy	E_b	120 GeV
bunch population	N_b	1.1×10^{11}
rms bunch length	σ_z	0.184 m
rms beam sizes	$\sigma_{x,y}$	$0.905, 1.32$ mm
rms momentum spread	δ_{rms}	0.43×10^{-3}
beta functions	$\beta_{x,y}$	33.85, 71.87 m
betatron tunes	$Q_{x,y}$	26.13, 26.185
chromaticities	$Q'_{x,y}$	0.1, 0.1
synchrotron tune	ν	3.23×10^{-3}
momentum compaction factor	α	1.2566×10^{-3}
circumference	C	6.911 km

and the average electron density in the vicinity of the beam was in the range of $1 \times 10^{11} m^{-3}$ to $5 \times 10^{12} m^{-3}$.

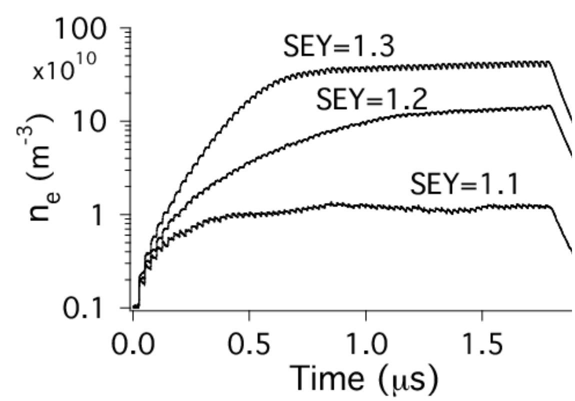

Figure 1: Average electron density versus time at a given station in the SPS (from a POSINST simulation).

SIMULATION OF ELECTRON BEAM DRIVEN INSTABILITY

We used the computer simulation codes Warp [5] and Headtail [6] to simulate an electron cloud driven transverse instability in the SPS, using the parameters given in table 1. Both codes used a continuous focusing model for the transverse and longitudinal dynamics of the beam in the lattice. In addition, Headtail had the option to apply a longitudinal focusing using a smooth function having the periodicity of the ring circumference, offering a more realistic localized focusing. The continuous versus localized longitudinal focusing in Headtail are controlled by the input parameter ”isyn”, taking the values 1 and 4 respectively. For these runs, there was 10 electron cloud stations per turn, and the transverse simulation box size was $20\sigma_x \times 20\sigma_y$.

figure 4 shows the beam fractional emittance growth versus turn number and the normalized power versus fractional tune for simulations using a uniform electron density of $n_e = 1 \times 10^{12} m^{-3}$. There is significant emittance growth, due to a transverse instability seeded by random particle noise. The three runs are in good agreement on the amount of emittance growth as well as on the average tune shift.

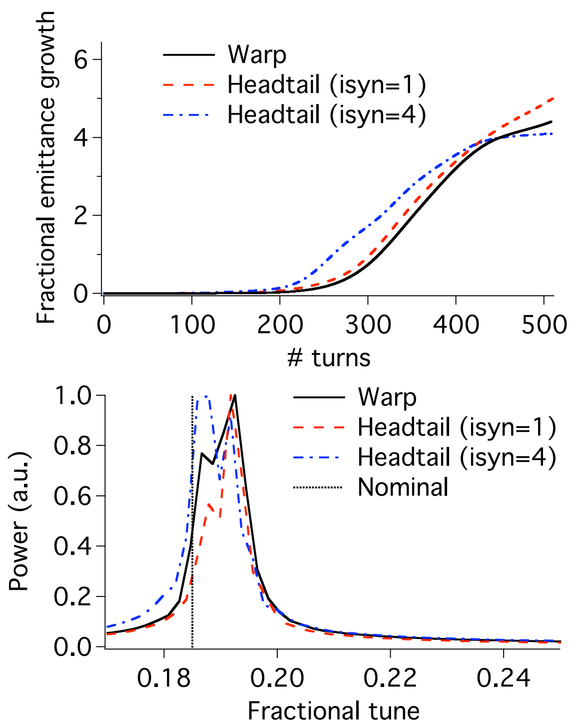

Figure 2: Beam emittance versus turn number (top) and normalized power versus fractional tune (bottom) from computer simulations of electron cloud driven instability using the codes Warp and Headtail. On the bottom plot, a dotted line indicates the location of the nominal vertical fractional betatron tune (0.185).

IDEALIZED MODELS OF FEEDBACK SYSTEMS

In order to explore numerically whether a feedback system can effectively mitigate the type of instability that was observed in the previous section, we have implemented three idealized feedback systems in Warp. All of them use as raw data snapshots of the average transverse displacement of regularly spaced beam slices, possibly weighted by the charge of each slice.

The first model of feedback substracts without delay the average transverse displacement multiplied by a factor α to the transverse position of the bunch macroparticles, interpolating linearly from the two neighboring slices according to their longitudinal position in the beam.

The second feedback model assumes that the average beam displacements evolves from one turn to the next according to the continuous focusing matrix

$$\begin{pmatrix} y \\ y' \end{pmatrix}^{n+1} = \begin{pmatrix} \cos(\sigma) & \beta \sin(\sigma) \\ -\sin(\sigma)/\beta & \cos(\sigma) \end{pmatrix} \begin{pmatrix} y \\ y' \end{pmatrix}^{n} \quad (1)$$

where σ and β are respectively the transverse phase advance for one turn and betatron function unperturbed by the electron clouds. The transverse displacement is recorded at one location in the ring for two consecutive turns i and $i+1$. From these quantities, that we label y_i and y_{i+1}, and with Eq. (1), we derive the transverse slope at i and $i+1$:

$$y'_i = \frac{y_{i+1} - y_i \cos(\sigma)}{\beta \sin(\sigma)}, \quad (2)$$

$$y'_{i+1} = -\frac{\sin(\sigma)}{\beta y_{i+1} + y'_i \cos(\sigma)}. \quad (3)$$

The transverse displacement at turn $i+2$ is predicted using y_{i+1}, y'_{i+1} and Eq. (1), and is used to correct the macroparticles transverse position at turn $i+2$ weighted by the factor α.

The third feedback model uses three consecutive records of the transverse displacement at turns i, $i+1$ and $i+2$ to estimate a perturbed phase advance and the slope at turn $i+2$:

$$\sigma = \arccos\left(\frac{y_i + y_{i+2}}{2y_{i+1}}\right), \quad (4)$$

$$y'_{i+2} = \frac{-y_i \cos(\sigma) + y_{i+1}\cos(2\sigma)}{\beta \sin(\sigma)}. \quad (5)$$

The transverse displacement at turn $i+3$ is predicted using σ, y_{i+2}, y'_{i+2} and Eq. (1), and is used to correct the macroparticles transverse position at turn $i+3$ weighted by the factor α.

An actual feedback system will have a finite bandwidth. Thus, optionally, a low pass filter (Heaviside function in k-space) with a cutoff at 1GHz was applied to the transverse displacement signal that was used for correcting the macroparticles transverse positions.

SIMULATIONS USING THE IDEALIZED FEEDBACK

We have performed simulations with the same parameters used in the previous sections, using one of the three feedback models, turning on or off the weighting of transverse displacement data by the slice charge, or the low pass filter with cutoff at 1GHz. For these runs, there was 100 electron cloud stations per turn, and the transverse box size was $7.7cm \times 2.25cm$.

The emittance growth history is shown for the simulated cases in Fig.3 for an initial background density of electrons $n_e = 1 \times 10^{12} m^{-3}$ and in Fig.4 for an initial background density of electrons $n_e = 5 \times 10^{12} m^{-3}$

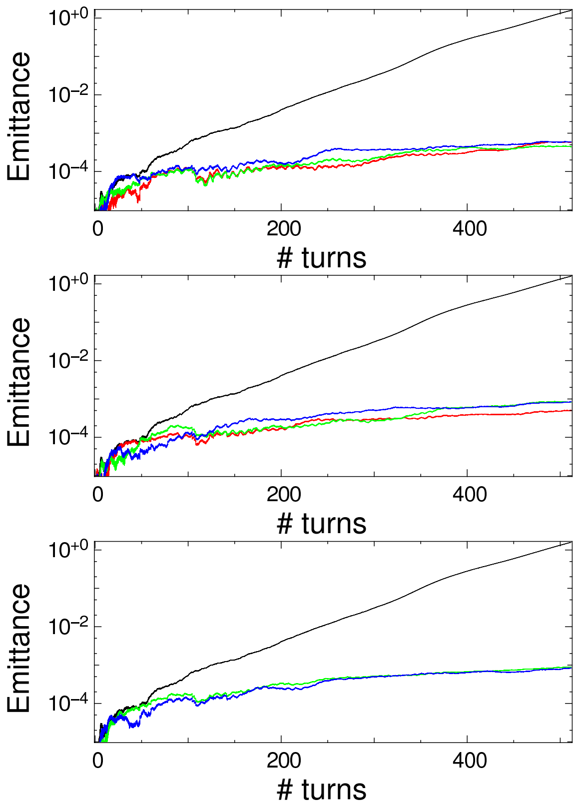

Figure 3: Beam emittance versus turn number from Warp simulations of a 120 GeV beam in the SPS with an initial background of electrons of $1 \times 10^{12}\mathrm{m}^{-3}$, with no feedback (black), feedback 1 (red), feedback 2 (green), and feedback 3 (blue), and with (top) no weighting, no filter, (middle) weighting, no filter, (bottom) weighting, lowpass filter with cutoff at 1GHz

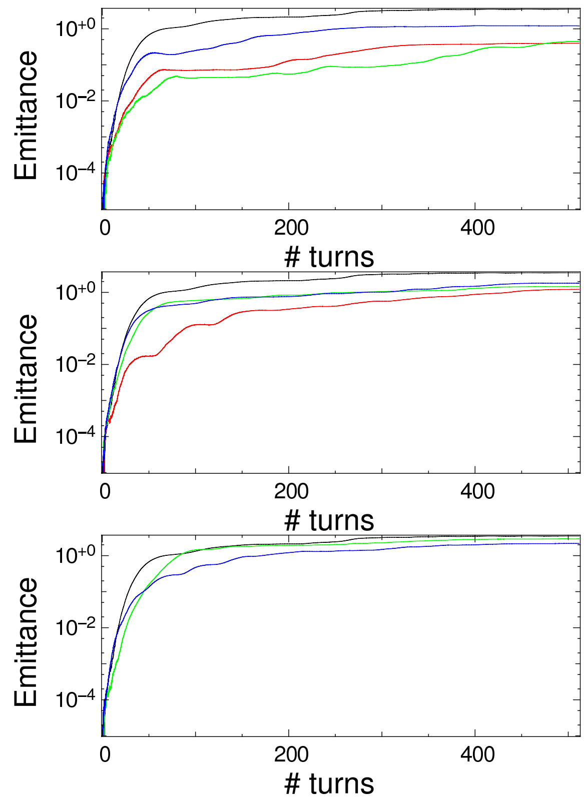

Figure 4: Same as Fig.3, but with an initial background of electrons of $5 \times 10^{12}\mathrm{m}^{-3}$.

For an electron background density of $1 \times 10^{12} m^{-3}$, all three feedback models damped the instability growth very effectively, while their effectiveness was much reduced at higher density, where the coefficient $\alpha = 0.1$ may be too small given the very rapid growth rate of the instability, and non-linear effects reduce the validity of the linear optics equations used to construct the feedback models 2 and 3.

CONCLUSION

We have explored via computer simulations the effect of electron clouds on a 120GeV bunch located in the tail of a batch in the SPS, and its mitigation using idealized models of feedback systems, considering two initial electron cloud densities at $1 \times 10^{12} m^{-3}$ and $5 \times 10^{12} m^{-3}$. The three idealized feedback systems were very effective at the lowest density that we used (which is already a relatively high density in practice), reducing the amount of emittance growth by more than three orders of magnitude after 500 turns. As might be expected, the effectiveness of the feedback models diminishes as the electron cloud density grows, assuming fixed characteristics for the feedback system. The successful mitigation of the instability at moderate electron cloud density supports the principle of using a feedback system to damp electron cloud instability in real accelerators. We are planning to extend this work to other bunch energies, more realistic descriptions of the focusing lattice using linear maps, and more realistic feedback models including smoother filtering functions, other gain factors, random noise, correction applied as a velocity kick.

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