SIMULATION OF E-CLOUD DRIVEN INSTABILITY AND ITS ATTENUATION USING A FEEDBACK SYSTEM IN THE CERN SPS*

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Abstract

Electron clouds have been shown to trigger fast growing instabilities on proton beams circulating in the SPS [1], and a feedback system to control the instabilities is under active development [2]. We present the latest improvements to the Warp-Posinst simulation framework and feedback model, and its application to the self-consistent simulations of two consecutive bunches interacting with an electron cloud in the SPS.

CODE IMPROVEMENTS AND FEEDBACK MODEL

Improvements have been made to the framework Warp-Posinst [3] toward higher efficiency, enabling self-consistent modeling of multi-bunch effects. Several features that exist in the Warp or Posinst core capability have been made accessible to the Warp-Posinst quasistatic model: mesh refinement (enabling more efficient field solving by concentrating the resolution where it is most needed); secondary emission of electrons at the walls; background gas ionization; and the option for using either Posinst or Warp routines for pushing electrons and detecting collisions at the chamber wall.

The feedback model that was presented in [4] was modified so that the action of the feedback now takes the form of a kick to the macro-particle velocity, rather than a displacement of the transverse position, similarly to the models presented in [5, 6]. The formula that is used to predict the correction is a generalization of the formula from [5], allowing the placement of the feedback kicker at any location in the ring, and the kick to be applied an arbitrary number of turns following the latest measurements. Assuming two measurements of the average transverse displacement y_{i-1} and y_i for a given slice of the bunch at two consecutive turns $i-1$ and i, the predicted average velocity offset of the slice at turn $i+\xi$ (the prediction is made at a different location when ξ is not an integer) is given, using the smooth focusing approximation, by

$$y'_{i+\xi} = \frac{(cc_\xi - ss_\xi)\, y_i - cy_{i-1}}{\beta_y s} \tag{1}$$

where $c = \cos(2\pi Q_y)$, $s = \sin(2\pi Q_y)$, $c_\xi = \cos(2\pi\xi Q_y)$, $s_\xi = \sin(2\pi\xi Q_y)$, and Q_y and β_y are respectively the vertical tune and beta function. A gain g is assumed and the correction applied at ξ on the bunch slice is given by $\Delta y'_{i+\xi} = -gy'_{i+\xi}$. For $\xi = 0$, the correction is applied at the same location and time of the second measurement and reduces to the formula given in [5]. $\xi = 1$ was used in the calculations presented in this paper, meaning that the correction was applied at the location of the measurements, with one turn delay. Finally, the feedback filter, which was previously a sharp cutoff in frequency space using FFTs, was replaced by a digital filter.

APPLICATION TO THE STUDY OF E-CLOUD EFFECTS IN THE SPS

The beam-electron-cloud interaction is modeled by a succession of N_s discrete interactions around the ring ("ecloud stations"). The modeling of two consecutive bunches propagating in the SPS at injection was performed, using the parameters from Table 1. In order to provide a consistent initial electron distribution, a prior build-up simulation using the code Posinst [7] was performed for a full train of bunches, and the electron distribution was dumped after the passage of bunch 34, chosen so that the electron induced tune shift of the subsequent bunches matched experimental data [2]. This particle dump was then used to initialize the Warp-Posinst simulation of bunches 35 and 36 (i.e. 6 buckets of 25 ns).

Table 1: Parameters Used for Warp-Posinst Simulations

beam energy	E_b	26 GeV
bunch population	N_b	1.1×10^{11}
rms bunch length	σ_z	0.23 m
rms transverse emittance	$\epsilon_{x,y}$	2.8, 2.8 mm.mrad
rms momentum spread	δ_{rms}	2×10^{-3}
bunch spacing	Δ_b	25 ns
beta functions	$\beta_{x,y}$	33.85, 71.87 m
betatron tunes	$Q_{x,y}$	26.13, 26.185
chromaticities	$Q'_{x,y}$	0, 0
Cavity voltage	V	2 MV
momentum compact. factor	α	1.92×10^{-3}
circumference	C	6.911 km
# of bunch slices/bucket	N_{slices}	64
# of stations/turn	N_s	10

Figure 1 shows a snapshot of the bunches and electron densities in the vertical plane, right after the passage of the bunches through the first station. The electron wake exhibits the focusing of the electrons by the bunches, producing high density spikes which result in jets of electrons impacting the walls and generating secondaries, eventually

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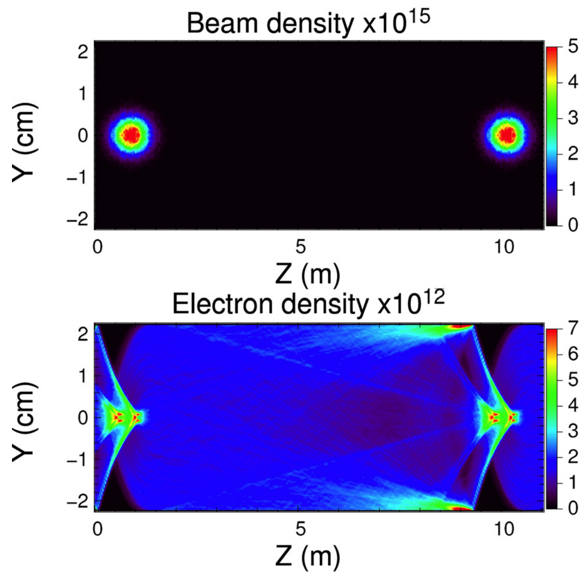

Figure 1: Charge density in the central vertical plane for the bunches (top) and the electrons (bottom). The bunches move from left to right.

relaxing to a nearly uniform background. A line plot of the electron density averaged over the pipe section reveals that the average electron density rises by about 8% from bunch 35 to 36.

Simulations were performed with the feedback turned off or on, with gains $g = 0.1$ and $g = 0.2$. The relative vertical emittance growth is shown in Fig. 2 (top) for the two simulated bunches. Both bunches experience a very rapid emittance growth when the feedback is off, which is heavily damped by the simulated feedback. Simulations with the feedback off and the feedback on with $g = 0.1$ were repeated with bunch 35 being frozen. The resulting emittance growth of bunch 36 are contrasted in Fig. 2 (bottom) with the ones obtained previously, showing similar emittance growth, and thus a weak influence of bunch 35 on 36.

In the simulations presented so far, the full bandwidth of the measured transverse displacement along the bunch slices was used to predict the feedback correction, without any filtering. However, a real feedback system will have a finite bandwidth. The simulations with the feedback on with $g = 0.1$ were repeated using five filters with cutoffs (filter gain ≈-3 dB) around 250, 300, 350, 450 and 575 MHz (see Fig. 3). The emittance growths are shown in Fig. 4 revealing that, for the filters that were used, a cutoff above 450 MHz was needed to provide maximum damping of the instability.

INFLUENCE OF NUMERICAL NOISE

For checking the consistency of the calculations, simulations of bunches 36 and 37 were performed, initialized with a dump of the electron distribution from a Posinst run after the passage of bunch 35. If all is consistent, the emittance growth of bunch 36 from such a simulation should match the emittance growth predicted for the same bunch 36 by the simulation of the (35,36) pair. However, the emittance growth of bunches 36 and 37 from the (36,37) run did match closely the ones from bunches 35 and 36 from the (35,36) run.

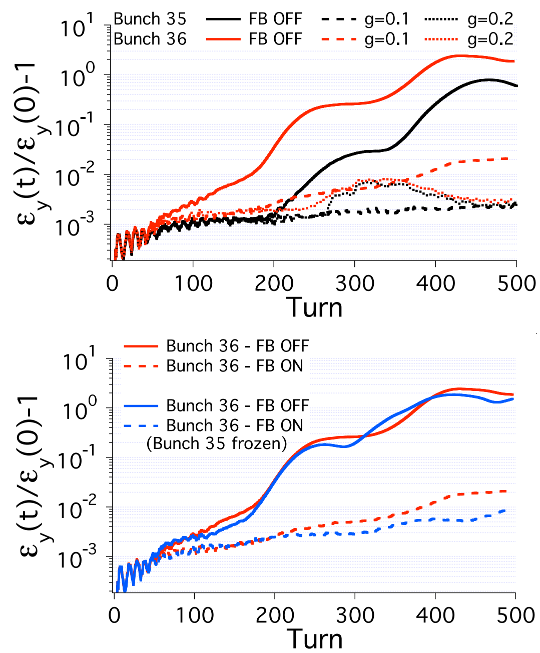

Figure 2: Relative emittance growth vs turn for: (top) bunches 35 (black) and 36 (red) with feedback OFF (solid) and ON with gain g=0.1 (dash) and g=0.2 (dot); (bottom) bunch 36 with full dynamics for bunch 35 (red) or a non-dynamical ("frozen") bunch 35 (blue) with feedback OFF (solid) and ON (dash) with gain g=0.1.

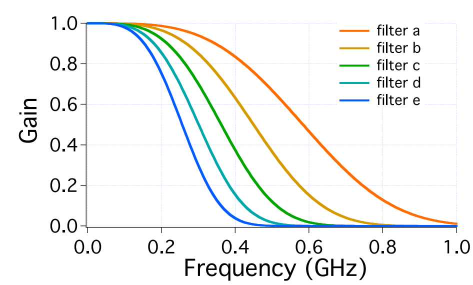

Figure 3: Frequency response of filters used in simulations with cutoffs (at -3dB) ranging from 250 MHz to 575 MHz.

To investigate this paradox, single bunch simulations were conducted with a bunch with four-fold symmetry, and initial electron macro-electrons (assumed to fill a uniform density $n_e = 10^{12}$ m^{-3}) being initialized (a) on a uniform grid; (b) randomly refreshed at each time step; (c) randomly using at each time step the distribution generated at t=0; (d) same as (c) and adding at each step random, one cell wide vertical displacements; (e) same as (d), and flipping randomly at each step the sign of the electrons hor-

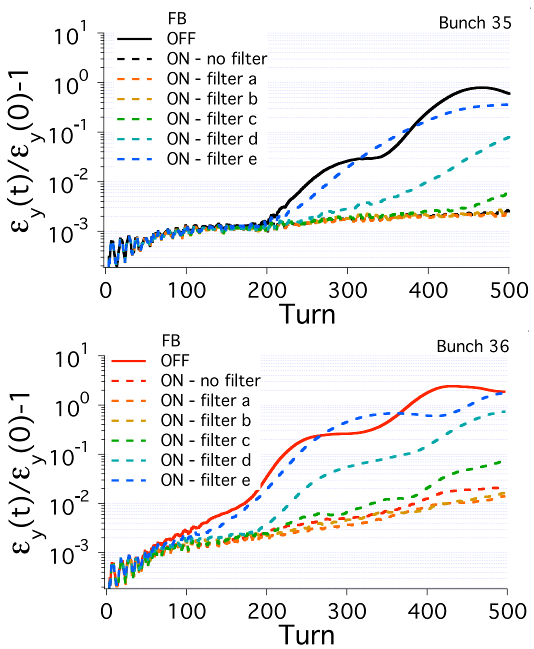

Figure 4: Relative emittance growth vs turn for bunches 35 (top) and 36 (bottom) with feedback OFF (solid) and ON (dash) with gain g=0.1 and various filters.

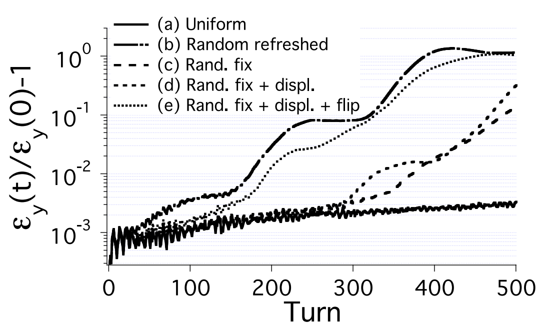

Figure 5: Relative emittance growth for single bunch simulations with various methods for injecting electrons.

izontal and vertical positions. The emittance growth obtained for each of theses cases is given in Fig. 5. With uniform loading, no seed is available for the vertical instability to develop and the small emittance growth is solely due to non-linear focusing (note that the amount of growth may not be physical since the number of stations $N_s = 10$ is not sufficient to resolve the betatron motion). With random loading, the vertical instability develops immediately if the distribution is refreshed with a different random load at each time step, but develops only around turn 300 if the same random distribution is used for the entire simulation. Adding short range randomness to the initial distribution still results in an onset around turn 300. Randomly flipping the sign of the electrons horizontal and vertical positions, which generates randomness at longer ranges, is more potent at provoking a much earlier onset. Additional tests (not shown) where short range noise was filtered in the deposited electron density used in the calculations, confirmed that long range rather than short range noise is most effective at triggering the instability.

By comparing the results obtained in this section with the ones obtained in the preceding one, we conclude that the lower emittance growth observed on bunch 35 was mostly due to injecting the same electron distribution at each time step, resulting in lower numerical noise than was experienced by bunch 36 which is subject to a different distribution of electrons at each time step, due to the random nature of the gas ionization and secondary emission processes. A technique based on random flipping of transverse positions of the injected electrons may be applied to put the two bunches on an equal footing with regard to numerical noise.

CONCLUSION

The Warp-Posinst framework has been augmented to allow for self-consistent multi-bunch simulations of the interaction of beams with electron clouds, and the simulated feedback model was improved. Simulations of two bunches circulating in the SPS showed effective damping of electron-cloudinduced transverse instability, provided that the bandwidth of the feedback has a cutoff at or above 450 MHz. Analysis of the sensitivity of the onset of the instability to numerical noise reveals that care must be exercised in the initialization of electrons and/or the analysis of emittance growth of a succession of bunches. In future work, numerical noise may be used as a proxy for noise that is present at various levels in the actual accelerator and feedback system.

Initial comparisons with experiment show good qualitative and some quantitative agreement on key aspects of the observed instability [2]. Work is underway for implementing a more realistic feedback model in Warp-Posinst using the same prediction algorithm that is to be used in the actual hardware.

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