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Self-Consistent Numerical Modeling of E-Cloud Driven Instability of a Bunch Train in the CERN SPS*

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Abstract

The simulation package WARP-POSINST was recently upgraded for handling multiple bunches and modeling concurrently the electron cloud buildup and its effect on the beam, allowing for direct self-consistent simulation of bunch trains generating, and interacting with, electron clouds. We have used the WARP-POSINST package on massively parallel supercomputers to study the growth rate and frequency patterns in space-time of the electron cloud driven transverse instability for a proton bunch train in the CERN SPS accelerator. Results suggest that a positive feedback mechanism exists between the electron buildup and the e-cloud driven transverse instability, leading to a net increase in predicted electron density. Comparisons to selected experimental data are also given.

INTRODUCTION

Electron clouds have been shown to trigger fast growing instabilities on proton beams circulating in the SPS [1] and other accelerators [2]. So far, simulations of electron cloud buildup and their effects on beam dynamics have been performed separately. This is a consequence of the large computational cost of the combined calculation due to large space and time scale disparities between the two processes. In [3], we have presented the latest improvements of the simulation package WARP-POSINST [4] for the simulation of self-consistent ecloud effects, including mesh refinement, and generation of electrons from gas ionization and impact at the pipe walls. We also presented simulations of two consecutive bunches interacting with electrons clouds in the SPS, which included generation of secondary electrons. The distribution of electrons in front of the first beam was initialized from a dump taken from a preceding buildup calculation using the POSINST code [5, 6, 7, 8]. In this paper, we present an extension of this work where one full batch of 72 bunches is simulated in the SPS, including the entire buildup calculation and the self-consistent interaction between the bunches and the electrons. Comparisons to experimental data are also given.

SELF-CONSISTENT SIMULATION OF ONE BATCH IN THE SPS

One batch of 72 consecutive bunches propagating in the SPS at injection was simulated for over 1000 turns of the machine, using the parameters given in Table 1 in the Appendix. A simulated bunch-to-bunch feedback system is used to stabilize the beam in the horizontal direction. No feedback system is used in the vertical direction. The simulation was performed on a parallel supercomputer using 2928 processors.

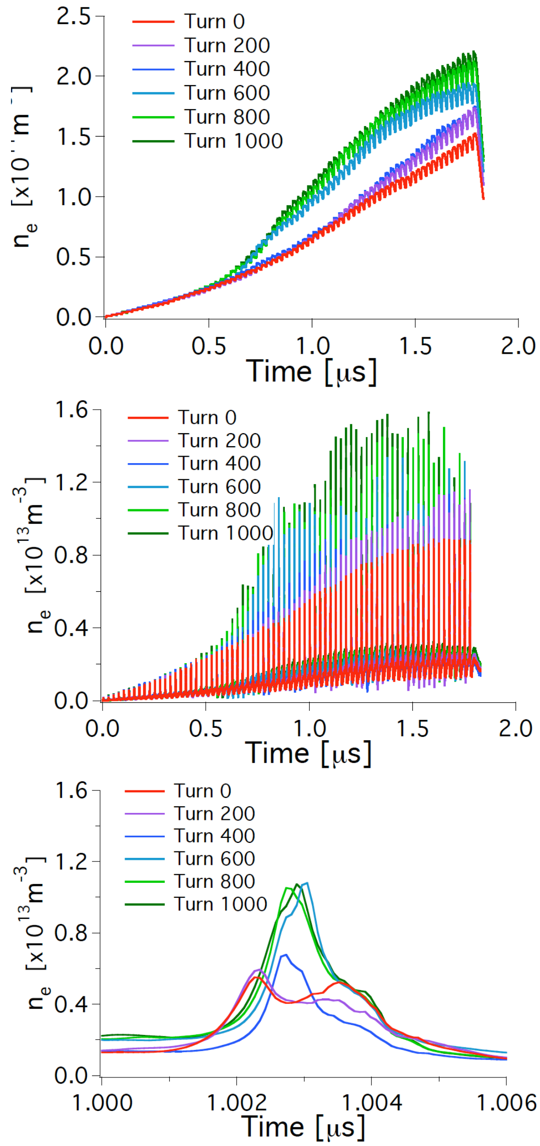

Figure 1: Time history of the charge density of electron cloud at one station around the ring: (top) averaged over the pipe section; (middle) on axis; (bottom) on axis between $1\mu s \leq t \leq 1.006\mu s$.

Time histories of the electron density averaged over the pipe cross section and on axis, taken at one location around

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the ring, are shown in Fig. 1, at turns 0 to 1000 by intervals of 200. There is an increase in average and on axis electron density between turn 200 and turn 600 for approximately the last two third of the bunch train, with an maximum enhancement of about 50% of the average electron density and 100% (i.e. doubling) of the electron density on axis.

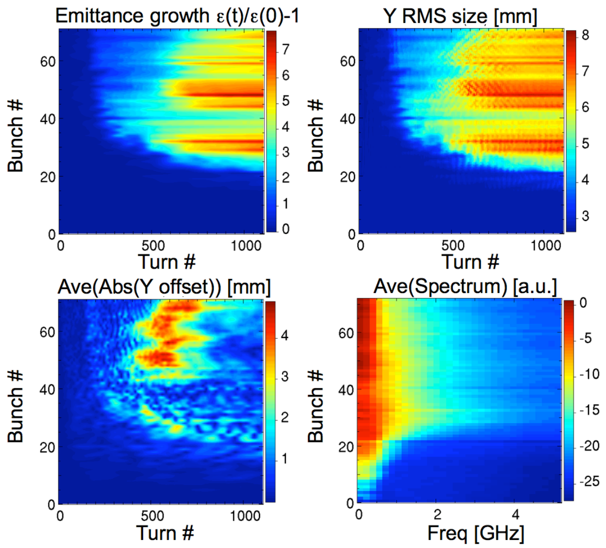

Figure 2: Bunch quantities vs bunch and turn numbers: (top-left) Bunch emittance growth ($\epsilon(t)/\epsilon(0) - 1$); (top-right) bunch vertical (Y) RMS size; (bottom-left) bunch vertical offset (averaged over all slices of absolute value of each slice offset); (bottom-right) spectrum of offset oscillations along the bunch (averaged over 1100 turns).

The turn-by-turn history of the bunches emittance, vertical RMS size and average vertical offset, as well as the averaged spectrum of vertical bunch slices oscillations, are given in Fig. 2. It shows substantial growth of emittance and vertical RMS size for bunches 25 and higher, starting to develop around turn 200 and saturating around turn 600. For bunches 40 and above, there is a net spike of average vertical offset between turn 500 and 600, followed by a steady decrease. This means that the increase that is observed in vertical emittance and RMS size is initially caused by coherent motion followed by incoherent motion due to phase mixing of the particle trajectories. For all bunches, most of the content of the vertical oscillations spectrum is below 500 MHz.

The onset of the instability around bunch 25 corresponds to a time of 25×25 ns$= 6.25$ μs after the passage of the first bunch at a fixed station, which matches the time at which the electron density increases in Fig. 1. Buildup simulations using the same parameters with POSINST (not shown) show that doubling the vertical dimension of the bunches lead to an increase by 20-30% of the average electron density. The higher increase that is observed in the fully self-consistent WARP-POSINST simulation might be due to taking into account temporal and spatial variations in the beam distributions that are not modeled in POSINST. This suggests that accurate prediction of electron buildup and their effect on the bunches necessitates the self-consistent simulation of both effects as presented in this paper.

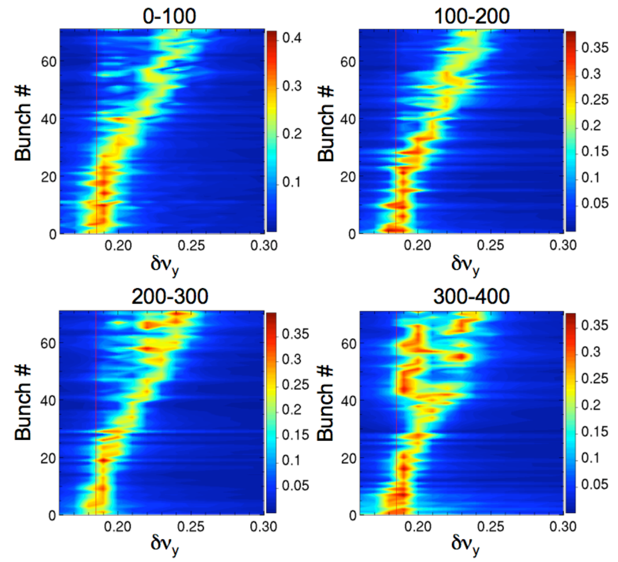

Figure 3: Bunch quantities vs bunch and turn numbers: (top-left) Bunch emittance growth ($\epsilon(t)/\epsilon(0) - 1$); (top-right) bunch vertical (Y) RMS size; (bottom-left) bunch vertical offset (averaged over all slices of absolute value of each slice offset); (bottom-right) spectrum of offset oscillations along the bunch (averaged over 1100 turns). For maximum visibility of the tune shift, the signal is normalized independently for each bunch.

The tune shift averaged over all slices of the beam and over 100 turns is given in Fig. 3 up to turn 400. The tune shift is limited between 0 and 0.005 for the first 25 bunches, then forks with one branch raising slowly up to about 0.015 and the second branch raising more rapidly up to about 0.05 for the bunches at the tail of the batch. Detailed analysis of the tune shift by regions of the bunches shows that the lower branch is preferentially associated with motion of the head and middle of the bunches while the higher branch is preferentially associated with motion of the tail.

COMPARISON WITH EXPERIMENT

The tune shift along the bunch for turns 100-200 is given in Fig. 4 for bunch 119 from measurements made in June 2009 [9], and for bunch 29 from the WARP-POSINST run. Bunch 29 from the simulation was chosen for the high degree of similarity of its tune shift pattern with the one of the experimental bunch 119. Both exhibit a higher tune shift in the tail than in the head, as expected with electron cloud driven instability, with both a fractional tune between 0.19 and 0.2 (nominal is 0.185). The fact that simulation tune shift of bunch 29 of batch 1 matches the tune shift of bunch 119 (bunch 47 in batch 2) suggests that the peak secondary electron yield of 1.2 that was used in the simulation might

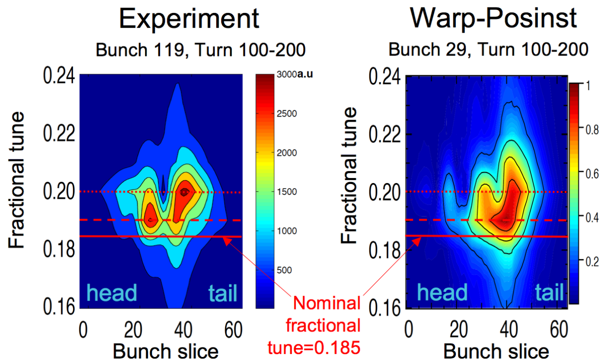

Figure 4: Fractional tune vs slice number for turns 100-200 from: (a) bunch 119 from experimental data (June 2009); (b) bunch 29 from WARP-POSINST simulation.

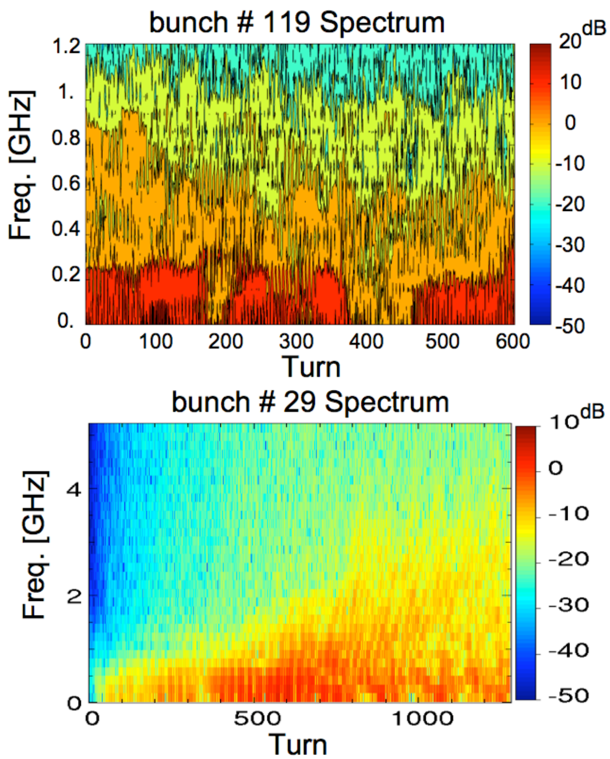

Figure 5: Vertical intra-bunch oscillations power spectrum vs turn number from: (top) bunch 119 from experimental measurements (June 2009); (bottom) bunch 29 from WARP-POSINST simulation.

be higher than the experimental one.

The turn-by-turn evolution of the spectrum of the transverse oscillations is given in Fig. 5 for bunch 119 of the experiment and bunch 29 of the simulation. In both cases, most of the content is located at the lowest portion of the frequency range. One notable difference is that the spectrum content is null initially and rises with time in the simulation while the content level is relatively constant in the experimental data. This suggests that the instability was already saturated on bunch 119 in the experiment when the data was recorded.

CONCLUSION

Direct self-consistent simulation of bunch trains generating, and interacting with, electron clouds where performed with the WARP-POSINST package on massively parallel supercomputers to study the growth rate and frequency patterns in space-time of the electron cloud driven transverse instability for a proton bunch train in the CERN SPS accelerator. Analysis of the turn-by-turn evolution of the electron buildup and of the bunches vertical motion shows that the vertical size increase of the bunches that is caused by its interaction with the electron cloud causes in return a net increase of up to 50% in average electron density and 100% in electron density on axis. This suggests that accurate prediction of electron buildup and their effect on the bunches necessitates the self-consistent simulation of both effects.

Comparison between selected data from the simulation and experimental data show points of good qualitative and quantitative agreement. One discrepancy resides in the level of instability with respect to bunch number with the batch train, which is tentatively attributed to a higher level of peak secondary yield in the simulations. Further analysis and simulations varying the physical and numerical parameters are underway.

APPENDIX

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}
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
bucket length	δ_b	5 ns
bunch spacing	Δ_b	25 ns
peak SEY	δ_{SEY}	1.2
# of bunches	N_{bunch}	72
# of stations/turn	N_s	10
# of slices/bucket	N_{slices}	64

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