Update on Electron-Cloud Simulations Using the Package WARP-POSINST*

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INTRODUCTION

At PAC05[1] and PAC07[2], we presented the package WARP-POSINST for the modeling of the effect of electron clouds on high-energy beams. We present here the latest developments in the package. Three new modes of operations were implemented: 1) a build-up mode where, similarly to POSINST (LBNL) or ECLOUD (CERN), the build-up of electron clouds driven by a legislated bunch train is modeled in one region of an accelerator; 2) a quasistatic mode where, similarly to HEADTAIL (CERN) or QuickPIC (USC/UCLA), the frozen beam approximation is used to split the modeling of the beam and the electrons into two components evolving on their respective time scales; and 3) a Lorentz boosted mode where the simulation is performed in a moving frame where the space and time scales related to the beam and electron dynamics fall in the same range. The implementation of modes (1) and (2) was primary motivated by the need for benchmarking with other codes, while the implementation of mode (3) fulfills the drive toward fully self-consistent simulations of e-cloud effects on the beam including the build-up phase.

BUILD-UP MODE

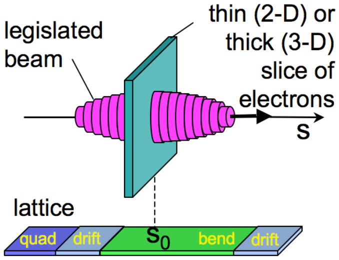

Figure 1: Sketch of the build-up mode. The dynamics of electrons is followed for a thin (2-D) or thick (3-D) slice located at a given location in the lattice, under the influence of a legislated particle beam passing through the slice.

In order to facilitate direct comparison with build-up codes like POSINST [4, 5, 6, 7], ECLOUD (CERN) or Cloudland (SLAC), a build-up mode class was implemented in Warp. In this mode, the dynamics of electrons is followed for a thin (2-D) or thick (3-D) slice located at a given location in the lattice, under the influence of a legislated particle beam passing through the slice (Fig. 1). Runs were performed with Warp and POSINST for the evolution of an electron cloud slice in the middle of a dipole. The average electron density history is given in Fig. 2 for a POSINST run and three Warp runs in: (a) 2-D, (b) 3-D with 4 cells longitudinally and a length of $0.2\sigma_z$, and (c) 3-D with 16 cells longitudinally and a length of $0.8\sigma_z$, where σ_z is the beam RMS length. For the 3-D runs, periodic boundary conditions were applied longitudinally for fields and particles. Snapshots of colored electron density plots and vertical phase space are given in Fig. 3, taken at $t = 130$ns. These results demonstrate a very good degree of agreement for electron cloud build simulations between POSINST, Warp in 2-D, and Warp in 3-D.

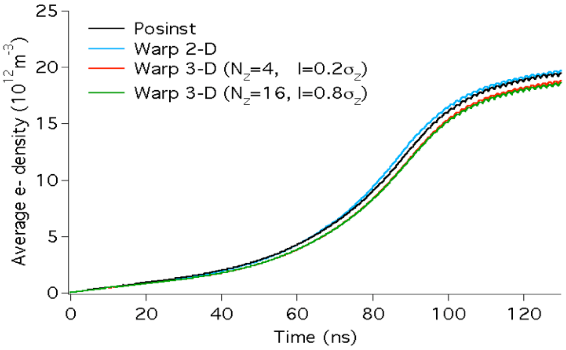

Figure 2: Average electron density versus time from POSINST and Warp in build-up mode simulations.

QUASISTATIC MODE

We have implemented a quasistatic [8] mode in Warp. In this mode, a 2-D slab of electron macroparticles is stepped backward (with small time steps) through the beam field (see Fig. 4). The 2-D electron fields (solved at each step) are stacked in a 3-D array, that is used to give a kick to the beam. Finally, the beam particles are pushed forward (with larger time steps) to the next station of electrons, using either maps or a Leap-Frog pusher. The first implementation was for accelerator lattices treated in the smooth approximation. A more detailed lattice description was implemented later (see below). This mode allows for direct comparison with the quasistatic codes HEADTAIL [9], QuickPIC [10], PEHTS [11] or CMAD [12]. The parallelization is mono-dimensional (along s) using pipelining, similarly to QuickPIC (see Fig. 5). We have simulated an e-cloud driven instability in an LHC-like ring with Warp in a quasistatic mode, and HEADTAIL. We used the parameters from table 1 in a drift (Fig. 6) and in a dipole (Fig. 7). Some of the parameters were purposely chosen to

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* Work supported by the US-DOE under Contract DE-AC02-05CH11231, the US-LHC LARP, and the US-DOE SciDAC program ComPASS. This work used resources of NERSC, supported by the US-DOE under Contract DE-AC02-05CH11231.

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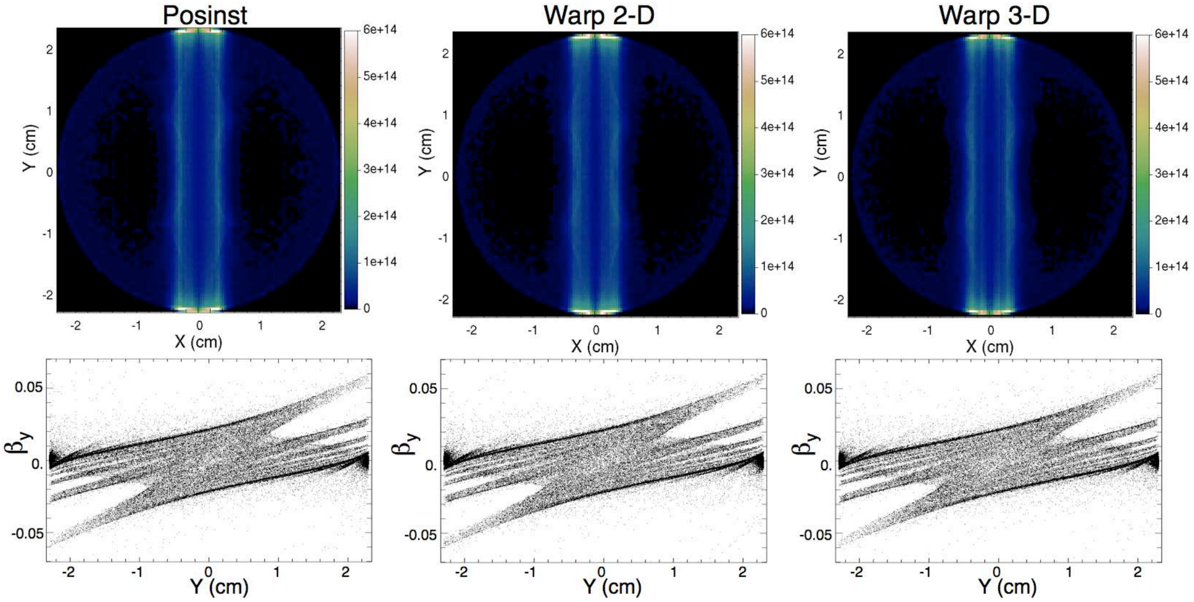

Figure 3: Snapshots of electron density and vertical phase space from build-up simulations using (left) POSINST, (middle) Warp in 2-D, (right) Warp in 3-D.

be unphysically large, so as to magnify their effects. The two codes predict similar emittance growth under the various conditions, with excellent qualitative agreement and good to very good quantitative agreement. We tentatively attribute the quantitative discrepancies to differences in implementations including: adaptive versus fixed grid sizes, different field solvers and particle pushers, different field interpolation procedures near internal conductors, slightly different values of physical constants, etc.

Table 1: Parameters used for simulations of e-cloud driven instability studies in the LHC.

circumference	C	26.659 km
beam energy	E_b	450 GeV
bunch population	N_b	1.1×10^{11}
rms bunch length	σ_z	0.13 m
rms beam sizes	$\sigma_{x,y}$	$0.884, 0.884$ mm
beta functions	$\beta_{x,y}$	$66., 71.54$ m
betatron tunes	$Q_{x,y}$	$64.28, 59.31$
chromaticities	$Q'_{x,y}$	$1000., 1000.$
synchrotron tune	ν	0.59
momentum compaction factor	α	0.347×10^{-3}
rms momentum spread	δ_{rms}	4.68×10^{-2}

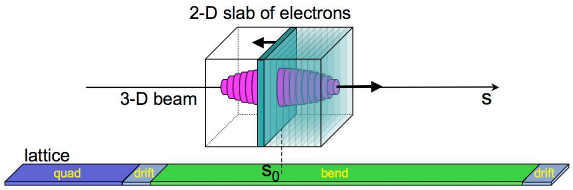

Figure 4: Sketch of the quasistatic mode. A 2-D slab of electron macroparticles is stepped backward (with small time steps) through the beam field. The 2-D electron fields (solved at each step) are stacked in a 3-D array, that is used to give a kick to the beam. Finally, the beam particles are pushed forward (with larger time steps) to the next station of electrons.

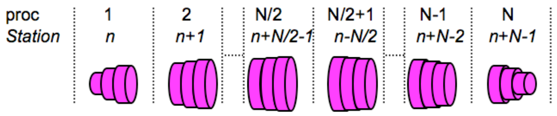

Figure 5: Sketch of the parallel decomposition for the quasistatic mode. The beam is distributed among n slices, that are uniformly spread among N processors. Using a pipelining algorithm, slices on a given processor are pushed from one station to the next, without waiting for the slices of the previous processors to reach the same station.

BOOSTED FRAME APPROACH

It was shown in [13] that it was possible to perform simulations of electron-driven instabilities from first principles (e.g. using standard Particle-In-Cell methods), at much reduced computing cost by performing the calculation in a suitable Lorentz boosted frame. Numerical developments that were needed have been implemented, including a new particle pusher and field solver, and are described in [14]. Special handling of inputs and outputs between the boosted frame and the laboratory frame are described in [15]. Two Warp calculations of an electron cloud driven instability

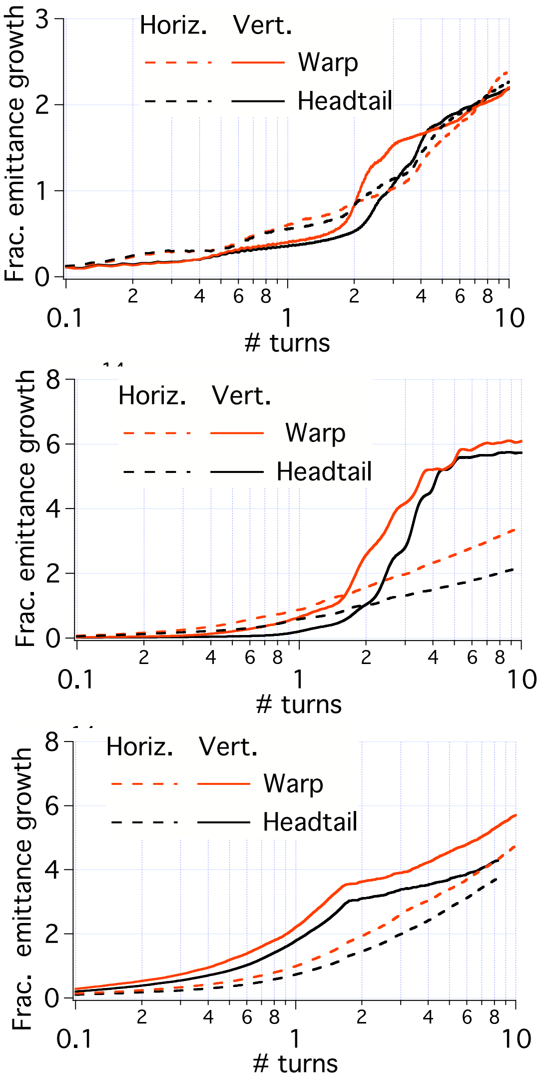

Figure 6: Fractional emittance growth from Warp (red) and HEADTAIL (black) simulations of an e-cloud driven instability in drifts of an LHC-like ring for an electron background density of $10^{14}m^{-3}$ for (top) $\nu = \alpha = \delta_{rms} = Q_x = Q_y = 0$, (middle) $Q_x = Q_y = 0$, (bottom) parameters from table 1.

showed very good agreement [14] between a full PIC calculation in a boosted frame and a calculation using the quasistatic mode, for similar computational cost.

FURTHER DEVELOPMENTS

We have recently added the capability to use linear maps to push particles in accelerator lattices, within the quasistatic mode and the full PIC mode in a Lorentz boosted frame. Good quantitative agreement was obtained between Warp using the quasistatic mode and CMAD [12]. Similar calculations with the full PIC method in a boosted frame are in progress.

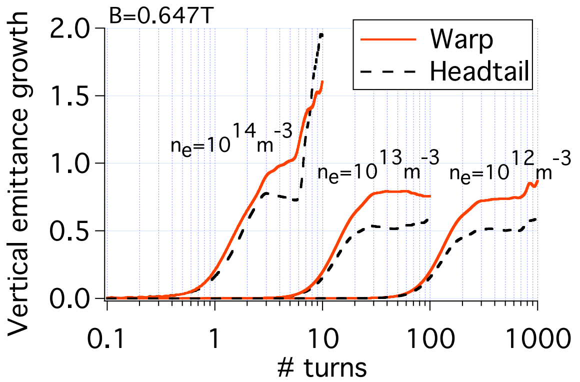

Figure 7: Fractional vertical emittance growth from Warp and HEADTAIL simulations in dipoles of an LHC-like ring for three assumed initial electron densities.

ACKNOWLEDGMENTS

We thank G. Rumolo for providing the source and invaluable support for using the code HEADTAIL.

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