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### Publication Date

2005-05-13

# Initial Self-Consistent 3D Electron-Cloud Simulations of the LHC Beam with the Code WARP+POSINST\*<sup>†</sup>

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## Abstract

We present initial results for the self-consistent beam-cloud dynamics simulations for a sample LHC beam, using a newly developed set of modeling capability based on a merge [1] of the three-dimensional parallel Particle-In-Cell (PIC) accelerator code WARP [2] and the electron-cloud code POSINST [3]. Although the storage ring model we use as a test bed to contain the beam is much simpler and shorter than the LHC, its lattice elements are realistically modeled, as is the beam and the electron cloud dynamics. The simulated mechanisms for generation and absorption of the electrons at the walls are based on previously validated models available in POSINST [3, 4].

## INTRODUCTION

Electron clouds and gas pressure rise limit the performance of many existing accelerators, and have the potential for limiting the performance of future storage rings [5], notably major machines such as the LHC and SNS. Over the past 10 years or so there has been a significant increase in the understanding of the electron-cloud effect (ECE) via simulations, with the goal of devising effective suppression mechanisms. A large body of results now exists based on two extreme “first-order” simulation models, which may be 2-D or 3-D. At one end, the beam is represented by a prescribed function of space and time, and the code simulates the dynamical evolution of the electron cloud, represented by macroparticles, under the action of successive bunch passages of the beam. At the other, the electron cloud is prescribed *ab initio* and the code describes the dynamical evolution of the beam, represented by macroparticles, as it traverses the electron cloud. The first approach allows the study of the electron cloud intensity and the space-time details of its distribution, while the second allows the assessment of emittance growth and beam instabilities. Both approaches have merits and deficiencies; however, in many cases, a dual approach based on the two extreme first-order codes may yield a sufficient amount of useful information on the ECE for a given machine.

Nevertheless, there are ECEs for which neither of the above-mentioned first-order approaches is sufficient, and a 3-D and/or self-consistent approach is essential for a quantitative understanding. Some examples are: the longitudinal flow of electrons, especially across lattice elements,

particularly for long-pulse beams; the interaction of the beam and electron cloud with residual and desorbed gas (ionization, charge exchange, secondary ionization, beam-particle-wall collisions, etc); and the long-time behavior of the dissipation of the electron cloud during a long beam gap, or following beam extraction.

Recently there has been progress towards self-consistent computer modeling, in which the electron cloud and the beam respond dynamically to each other as they evolve in time and space. Although such a description is more realistic than the above-mentioned first-order approaches, the computational cost is much higher, as the full potential of the self-consistent approach is probably not fully realized until one considers fully 3-D models for the entire accelerator in question, or at least for large portions of the machine. In addition to the large physical size of the simulation domain, large number of macroparticles (both for electrons and for beam particles) are required, as well as 3-D electromagnetic field solvers and good descriptions of the geometry and physical-electronic properties of the vacuum chamber. In practice, the large scale of the problem almost demands the use of modern computational techniques such as adaptive mesh refinement, multigrid schemes, multiscale techniques in the time domain, along with visualization techniques, modular coding, and the use of massively parallel computers. Examples of codes under current development and/or testing that include self-consistent features to a lesser or greater extent are given in Ref. [6].

Presently we are participating, as part of a collaboration between LBNL, LLNL, UC Berkeley and Tech-X Corp., in an integrated R&D program [7] of dedicated diagnostics, measurements, and simulations of ECEs centered around the HCX facility at LBNL [8]. Such facility was initially conceived as a prototype for a heavy-ion fusion driver, and currently operates with  $K^+$  beams of energy  $\sim 1-2$  MeV/ion, pulse length  $\sim 5$   $\mu$ s, and intensity  $\sim 5 \times 10^{13}$  ions/pulse. The HCX is primarily dedicated to beam dynamics studies of space-charged dominated heavy-ion beams. Although beam transport at the HCX has been analyzed for some time with the code WARP [2], the new hardware and instrumentation allows adding electrons in a more-or-less controllable way, and measuring various features of the electron, gas, or ion densities, in addition to the beam phase space.

## LHC FODO CELL SIMULATION

As part of our R&D program, we are developing a self-consistent 3-D electron-cloud code based on the merge [1]

\* Work supported by the U.S. DOE under LLNL and LBNL contracts W-7405-Eng-48 and DE-AC03-76F00098.

<sup>†</sup> Proc. PAC05 (Knoxville, 16–20 May 2005), paper FPAP016.

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of WARP [2] and POSINST [3]. Our merged code, with the provisional name of WARP+POSINST, is being actively validated via methodical comparisons against experiments at the HCX. As is the case with other electron-cloud codes, WARP+POSINST can be usefully applied to machines that operate in entirely different parameter regimes. As an example, here we report on a first application to the LHC. For this purpose, we have chosen a single arc FODO cell traversed repeatedly by a single proton bunch.

The magnetic fields in the FODO cell used in our simulation have nominal values for 7 TeV beam energy, with geometry, dimensions and optics as specified in the LHC CDR [9]. However, for the purposes of this first test, we have used the following simplifications: (1) all cell magnets other than dipoles and quadrupoles are not included (actually, replaced by drifts); and (2) magnetic edge fields are neglected. As for the beam, we represent it by a single bunch with nominal intensity and emittances, but we use the following simplifications: (3) periodic boundary conditions in the longitudinal dimension, both for the beam and for the electrons (so that, effectively, the model represents a circular “storage ring” consisting of a single FODO cell); and (4) the energy spread is zero (all particles have nominal energy).

We consider here only one source of primary electrons, namely the photoelectric effect from synchrotron radiation striking the walls of the chamber because, at top energy, this mechanism is by far the dominant one. We assume that the effective quantum efficiency is 0.1, so that  $1.27 \times 10^{-3}$  photoelectrons are generated on the chamber surface per proton per meter of beam traversal, and that the effective photon reflectivity is 20% (i.e., 80% of the photoelectrons are generated on the illuminated part of the beam screen, while 20% are generated uniformly around the perimeter of the beam screen cross-section). Finally, we set the secondary emission yield to zero.<sup>1</sup> Results are shown in Fig. 1, which shows one frame of a simulated digital movie.

## DISCUSSION

In the LHC FODO cell simulation described above, there is a negligible effect from the electrons on the beam for two reasons: (a) the elapsed time in the movie (maximum 3 bunch passages of the beam through the FODO cell) is far too brief; and (b) the electron-cloud density is far lower than what is realistically expected at the LHC, owing to the absence of secondary emission. For these reasons, our LHC simulation approximates very closely the first class of first-order simulations discussed in the introduction, and our current results are in qualitative agreement with those from earlier first-order simulations. We are planning a program of simulations for ever more realistic models for the LHC and other machines, including dynamical vacuum ef-

<sup>1</sup>For the purposes of simulated movies, all macro-electron charges must be set equal. This constraint quickly leads to unmanageable numbers of macroparticles unless the secondary emission yield is set unrealistically low, hence we have set it to 0 as a first case.

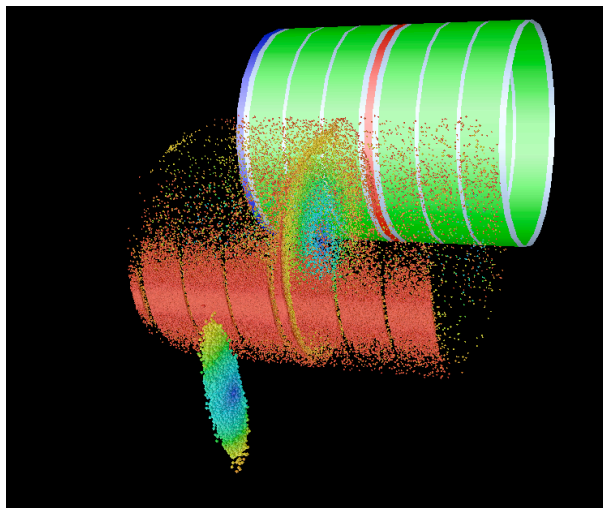


Figure 1: (color) LHC arc FODO cell simulation: one frame of a simulated digital movie of the electron cloud in a FODO cell. The chamber, electron cloud, and beam are shown separately for clarity. The top plot is a sketch of the cell magnets (green: dipoles; blue: focusing quad; red: defocusing quad; silver: drift). Although the cross-section is cylindrical in the sketch, the simulation uses the actual shape for the beam screen (cylinder with flattened top and bottom). The lower-left set of particles (mostly blue-green), represents the proton beam, moving from left to right (shown much magnified in the transverse dimensions). The middle set of particles (mostly red) represents the electrons in the chamber at the time instant when the beam traverses the defocusing quad. This frame is from the 2nd passage of the bunch through the cell; the electrons seen to the right of the bunch are left over from the 1st passage. The density of electrons is much higher on the near side, corresponding to the illuminated region.

fects from desorbed gas and ionization of residual and desorbed gas.

The digital movie described above, showing 3 passages of one bunch through one FODO cell, took  $\sim 8$  h wall-clock time to complete on a 2.5 GHz Macintosh G5 workstation (the proton bunch was represented by 100,000 macroparticles, and one electron macroparticle represented one million real electrons). However, WARP runs on parallel computers, including SEABORG, a massively parallel (6080 processors) computer at NERSC, using MPI. Therefore, while scalability tests remain to be carried out for this particular problem, we are confident that much larger and more realistic simulations are well within our reach.

## ACKNOWLEDGEMENTS

We are grateful to NERSC for supercomputer support.

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- [6] Brief descriptions and further references for several codes can be found in the following contributions to Ref. [5]: QUICKPIC: A. Ghalam et. al.; ORBIT: A. Shishlo et. al.; CSEC: M. Blaskiewicz et. al.; BEST: H. Qin et. al.; PARSEC: A. Adelman et. al.; CLOUDLAND: L. Wang et. al.; PEI: K. Ohmi et. al.
- [7] For a current status of activities, see the following papers in these proceedings: J.-L. Vay et al, paper ROPB006 (Ref. [1]); P. Seidl et. al., paper FPAP015; S. A. Veitzer et. al, paper FPAP021; M. Kireef-Covo et. al., paper FPAP033; A. Molvik et. al., paper ROPB002; R. Cohen et. al., paper ROPA009.
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