New simulation capabilities of electron clouds in ion beams with large tune depression*

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Abstract

We have developed a new, comprehensive set of simulation tools aimed at modeling the interaction of intense ion beams and electron clouds (e-clouds). The set contains the 3-D accelerator PIC code WARP and the 2-D "slice" e-cloud code POSINST [M. Furman, this workshop, paper TUAX05], as well as a merger of the two, augmented by new modules for impact ionization and neutral gas generation. The new capability runs on workstations or parallel supercomputers and contains advanced features such as mesh refinement, disparate adaptive time stepping, and a new "drift-Lorentz" particle mover for tracking charged particles in magnetic fields using large time steps. It is being applied to the modeling of ion beams (1 MeV, 180 mA, K+) for heavy ion inertial fusion and warm dense matter studies, as they interact with electron clouds in the High-Current Experiment (HCX) [experimental results discussed by A. Molvik, this workshop, paper THAW02]. We describe the capabilities and present recent simulation results with detailed comparisons against the HCX experiment, as well as their application (in a different regime) to the modeling of e-clouds in the Large Hadron Collider (LHC).

INTRODUCTION

The steadily increasing beam intensity required in operational and upcoming accelerators leads to growing concerns over the degradation of beam emittance due to electron cloud effect and gas pressure rise [1]. Accurate prediction necessitates a detailed understanding of the physical processes at play with a quantification of the relative importance of various effects. To this end, the development of a new generation of computer simulation code is underway, in conjunction with detailed measurements from a heavily diagnosed small dedicated experiment, for extensive benchmarking and code validation. We provide a brief overview of the simulation code and the dedicated experiment, and present recent results, focusing on the dynamics of electrons in a magnetic quadrupole.

* This work was supported by the Director, Office of Science, Office of Fusion Energy Sciences, of the U.S. Department of Energy under Contracts No. DE-AC02-05CH11231 and No. W-7405-Eng-48 and by the US-LHC accelerator research program (LARP).

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A UNIQUE COMBINATION OF SIMULATION AND EXPERIMENTAL TOOLS

THE WARP/POSINST SIMULATION PACKAGE

The simulation tool is based on a merge of the Heavy Ion Fusion [2] accelerator code WARP [3] and the High-Energy Physics electron cloud code POSINST [4, 5], supplemented by additional modules for gas generation and ionization [6], as well as ion-induced electron emission from Tech-X package TxPhysics [7]. The package allows for multi-dimensional (2-D or 3-D) modeling of a beam in an accelerator lattice and its interaction with electron clouds generated from photon-induced, ion-induced or electron-induced emission at walls, or from ionization of background and desorbed gas. The generation and tracking of all species (beams particles, ions, electrons, gas molecules) is performed in a self-consistent manner (the electron, ion and gas distributions can also be prescribed if needed for special study or convenience). The code runs in parallel and benefits from adaptive mesh refinement [8], disparate adaptive time-stepping and a new "drift-Lorentz" particle mover for tracking charged particles in magnetic fields using large time steps [9]. These advanced numerical techniques allow for significant speed-up in computing time (orders of magnitude) relative to brute-force integration techniques.

THE HIGH CURRENT EXPERIMENT

The High Current Experiment [10], located at Lawrence Berkeley National Laboratory, consists of one injector producing singly charged Potassium ion beams (K+) at 1 MeV, followed by a transport lattice made of a matching section, a ten-quadrupole electrostatic section and a four-quadrupole magnetic section. The flat top of the beam pulse reaches 180 mA and its duration is 4 μs (see Fig. 1). Note that the tune depression is approximately 0.1.

We study electron effects in the magnetic section [11, 12], shown in Fig. 2. A suppressor ring electrode, surrounding the beam after it exits the last quadrupole magnet, can be biased to -10 kV to prevent ion-induced electron emission off an end wall (a slit plate) from reaching the magnets, or can be left unbiased to allow electrons emitted from the end wall to freely flow upstream into the magnets. There is also a series of three clearing electrodes,

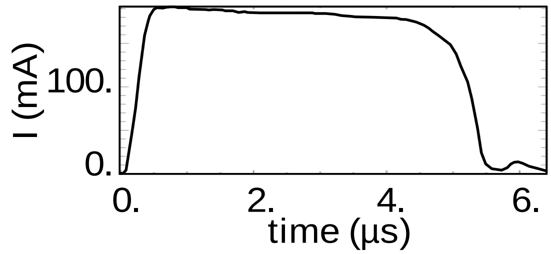

Figure 1: Beam current history recorded from Faraday cup measurement at the exit of the electrostatic section (entrance of the magnetic section).

labeled (a), (b) and (c) in Fig. 2, in the drift regions between quadrupole magnets, which can be biased positively to draw off electrons from between any pair of magnets. The current that flows in and out of these clearing electrodes is monitored in the experiment and is compared to simulation results for benchmarking.

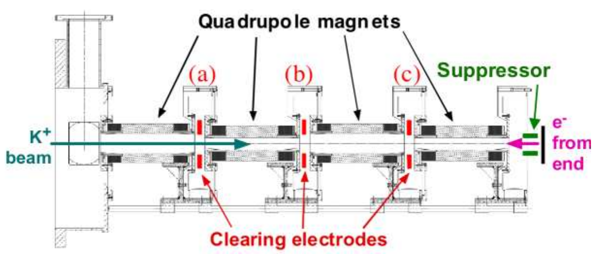

Figure 2: HCX in region of 4 quadrupole magnets, with clearing electrode rings between magnets and a suppressor electrode ring after the last magnet.

RECENT STUDY OF DYNAMICS OF ELECTRONS IN A MAGNETIC QUADRUPOLE

For convenience, we label the electrons created by the beam hitting the end wall as “primary”, while we label the electrons created by the primary electrons hitting the vacuum pipe surrounding the magnets as “secondary” (these encompass any subsequent generation of electrons). The primary electrons created at the end plate and propagating upstream can enter only two quadrants of the fourth (last) magnet, because of the sign of the $\mathbf{E} \times \mathbf{B}$ drift, and then drift upstream. The current from clearing electrode (c) is compared with simulation in Fig. 3, in the case where the suppressor ring electrode was left grounded to allow electrons to propagate upstream, and the three clearing electrodes were biased to $+9$ kV. The simulation and experimental results agree on the magnitude and frequency (around 10MHz) of the observed oscillations.

Simulation results reveal that these time-dependent oscillations recorded on clearing electrode (c) are related to bunching of electrons drifting upstream in the fourth magnet. The effect of electrons bunching is revealed on the plot of line charge densities in Fig. 4 where oscillations of large amplitude and wavelength of approximately 5 cm are observed in the electron density in the fourth magnetic quadrupole. The effect is so pronounced that at the peak the electron line charge density reaches 1.5 times the beam line charge density. The bunching of electrons itself is revealed in Fig. 5 where electrons bunches are easily observable from the middle of the quadrupole and upstream. The over-neutralization of the beam space-charge by these electron bunches is evident in Fig. 6 where islands of negative potential are formed at the location of the bunches. Although some possible candidate explanations have been eliminated (electron-ion two-stream instability for example) the nature of these oscillations has not yet been firmly identified and other possibilities, such as the Kelvin-Helmholtz instability, are under active investigation.

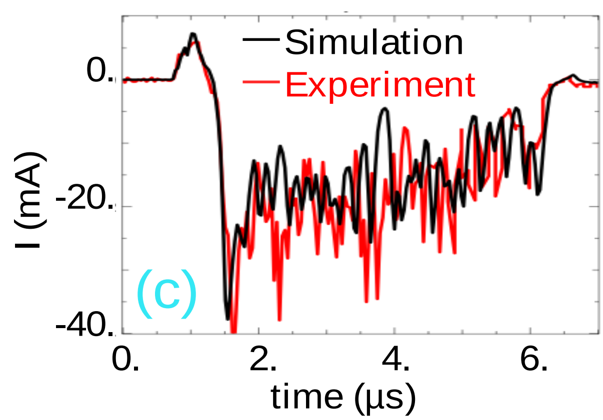

Figure 3: Current history at clearing electrodes (c): red - recorded on HCX experiment, black - WARP-POSINST simulation of HCX.

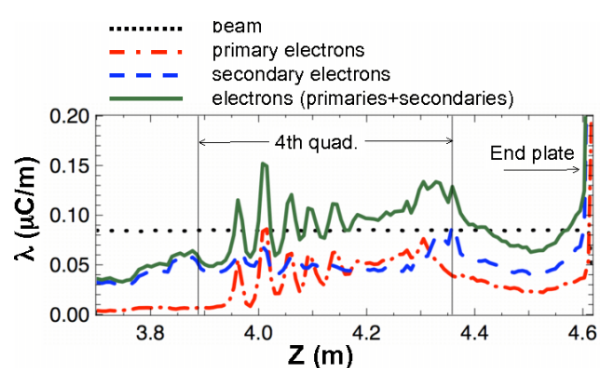

Figure 4: Line charge density λ (absolute value), from WARP-POSINST simulation of HCX at $t = 3$ μs.

CONCLUSION, FUTURE DIRECTIONS

We have developed a three-dimensional self-consistent code suite which includes advanced numerical methods,

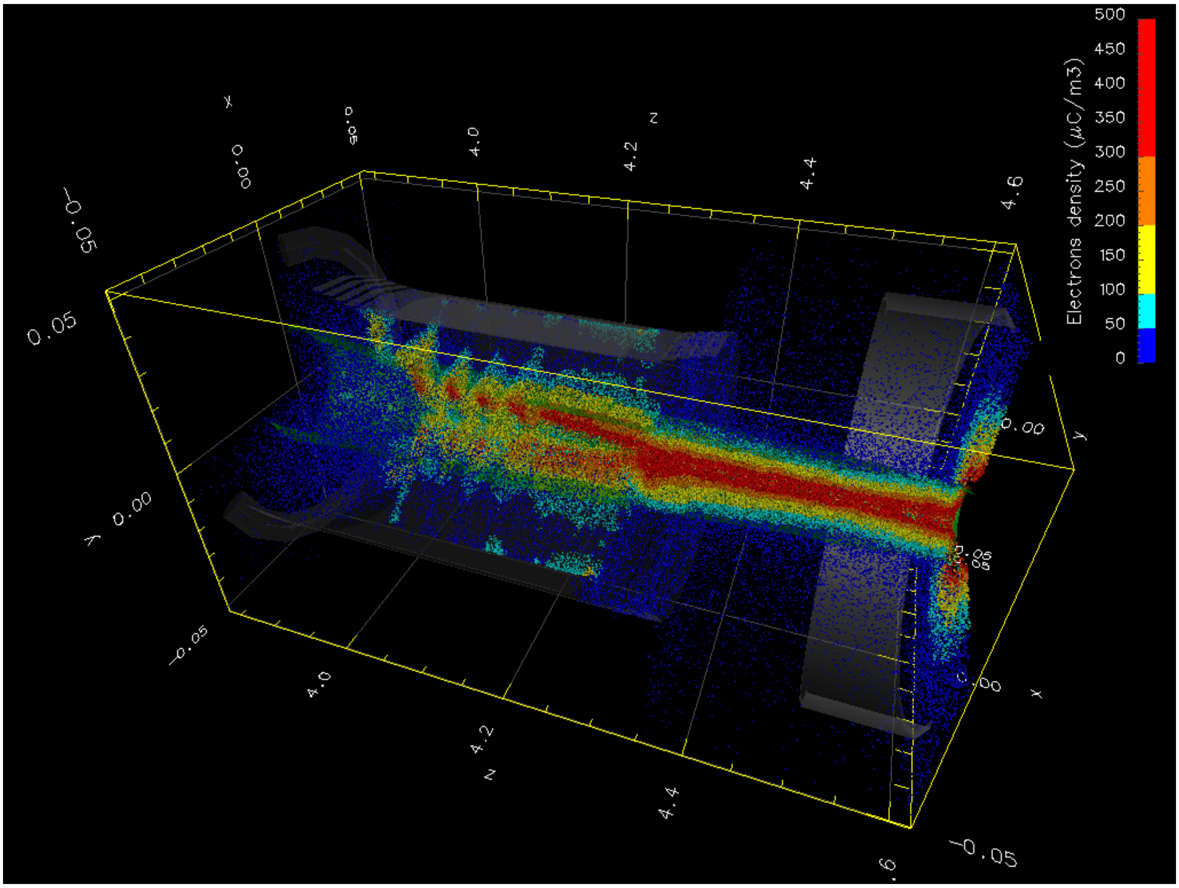

Figure 5: Snapshot of electron macroparticles, colored according to charge density (absolute value), from WARP-POSINST simulation of HCX at $t = 3\ \mu$s.

allowing the modeling of configurations which were out of reach with previously available tools. Benchmarking against the HCX experiment has provided some very good qualitative and quantitative agreements, and is being pursued actively in order to fully validate the code and the embodied physical model. We have also applied the WARP-POSINST code to the modeling of a train of bunches in one LHC FODO cell (Fig. 7). While it will be a valuable tool to study in detail the beam and electron clouds for many turns, the 3-D self-consistent approach, even with the mesh refinement and advanced particle pusher capabilities, cannot simulate the thousands of turns (or more) that are required for the modeling of slow emittance growth [13], which is a growing concern for LHC. Thus we will implement a mode of operation similar to the one in the HEADTAIL code, for example, where the beam is followed in three dimensions while the electrons are represented as two-dimensional slices passing through the beam.

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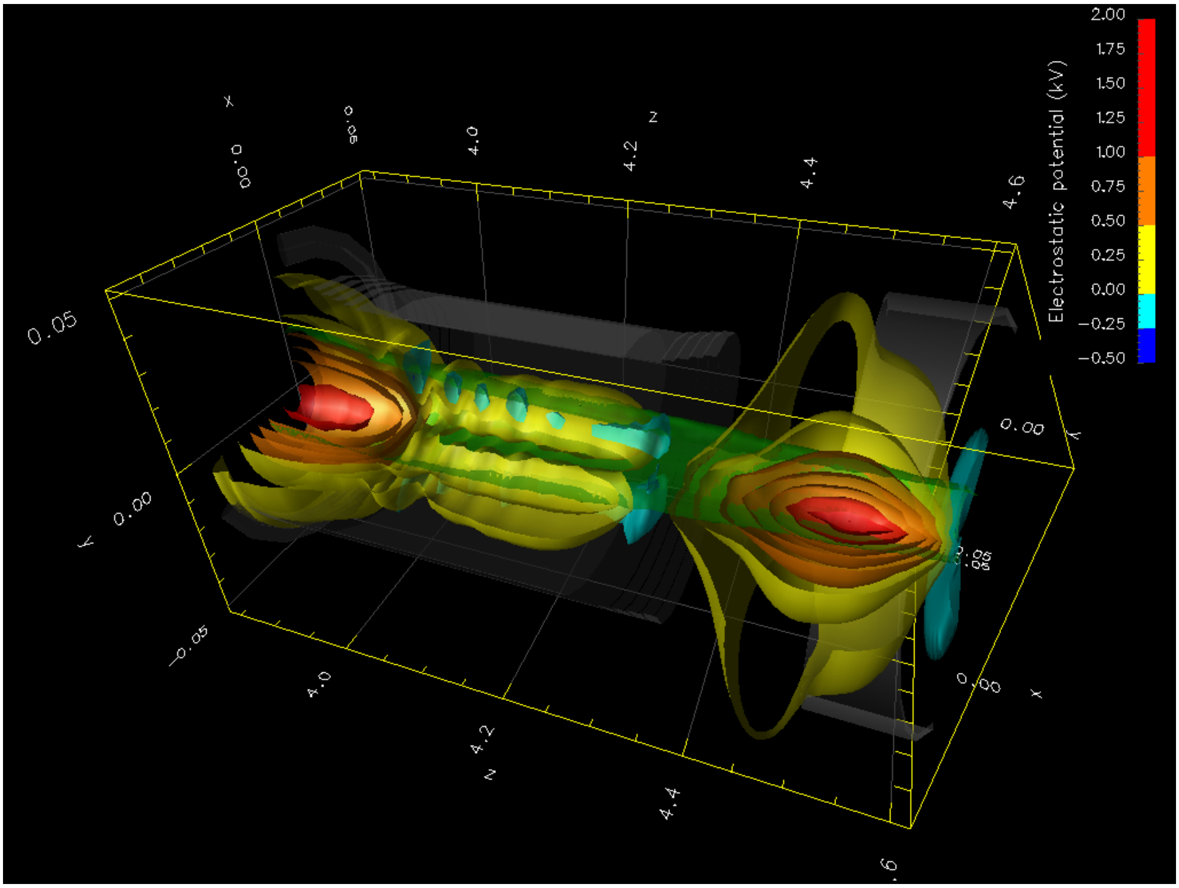

Figure 6: Snapshot of equipotential surfaces from WARP-POSINST simulation of HCX at $t = 3$ μs.

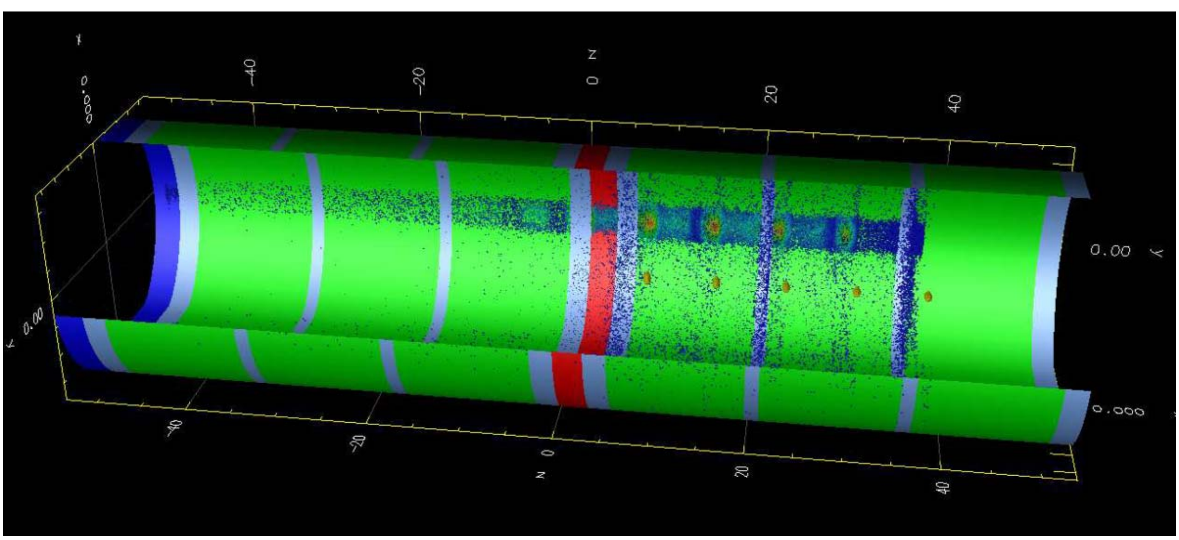

Figure 7: Snapshot from a 3-D self-consistent simulation of five bunches (yellow) propagating (from left to right) in one LHC arc FODO cell (green: dipoles; blue: focusing quad; red: defocusing quad; silver: drift) and interacting with electrons. The electrons are generated by photo-emission (80% direct synchrotron emission from the bunches plus 20% background radiation) and secondary emission, and are colored according to electron density (rainbow palette; low: blue; high: red).