ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPMA037



# ELECTRON CLOUD BUILDUP AND DISSIPATION MODELS FOR PIP-II *

S. A. Veitzer†, Tech-X Corporation, Boulder, CO, 80303 USA
P. H. Stoltz, Tech-X Corporation, Boulder, CO, 80303 USA

*Abstract*

Buildup of electron plasmas in accelerator cavities can cause beam degradation and limit performance in high-intensity circular particle accelerators. This is especially important in machines such as the LHC, and PIP-II, where mitigation techniques such as beam scrubbing in order to decrease the SEY are expensive and time consuming. Modeling of electron cloud buildup and dissipation can provide understanding as to the potential negative effects of electron clouds on beam properties, as well as estimates of the mitigation required to maintain accelerator performance and beam quality as accelerators move to higher intensity configurations. We report here on simulations of electron cloud buildup and dissipation for geometry, beam and magnetic field configurations describing the Recycler at Fermilab. We perform electrostatic simulations in 3D with VSim PIC, including the effects of space charge and secondary electrons. We quantify the expected survival rate of electrons in these conditions, and argue that improvements in reducing the SEY is unlikely to mitigate the electron cloud effects.

## ELECTRON CLOUD SURVIVAL RATE IN CIRCULAR ACCELERATORS

In circular accelerators, electron clouds may build up from very low densities as trains of bunches pass through the accelerator. As each bunch passes, electrons experience the potential of the beam and are accelerated through the center of the beam pipe to the opposite wall. Typically they will gain enough energy to produce secondary electrons, which are in turn accelerated by the next bunch.

This process produces a build up of an electron plasma, which saturates at a density that is some large fraction of the linear charge density of the beam [1], depending on the bunch length and the cross-sectional size of the beam pipe. At saturation, electrons near the beam pipe walls are shielded from the beam potential by other electrons, and are not significantly accelerated to produce more secondaries. Also, electrons that are accelerated by the passing beam encounter space charge due to these electrons and so impact the walls with lower energy, which can reduced overall secondary yields.

Electron clouds dissipate during the period of time when there are no bunches crossing, as they drift to beam pipe walls with energies low enough that they do not produce significant secondary electrons. The dissipation typically occurs very swiftly, with the number of electrons decreasing exponentially. However, without the influence of additional bunch crossings, some electrons will have very low energies, and will drift for long enough that they are present when the first bunch in the beam returns.

## ELECTRON CLOUD BUILD UP AND DISSIPATION NUMERICAL MODELS

Electron cloud build up has previously been modeled using a variety of high-performance Particle-In-Cell (PIC) codes, including Vorpal [1–3], WARP coupled with POSINST [4–6] and others. Build up simulations have typically focussed on the saturation density, and dynamics of electron cloud evolution under different magnetic field configurations e.g. [7], and the effects of different wall materials on overall cloud densities e.g. [8]. Here, we focus on the build up and dissipation aspects of electron clouds, in order to understand the survival rate of electrons over more than a single revolution period.

We use the plasma simulation package VSim [9], which employs the Vorpal simulation engine [10] to model electron cloud build up, dynamics, and dissipation. Our models use the following physical parameters, corresponding to the Fermilab Recycler storage ring. We simulate the crossing of 504 Gaussian-shaped bunches (84 bunches per batch and 6 batches per beam) with bunch lengths of 60 cm, bunch spacing of 18.94 ns, beam radius of 3.0 mm, and $5.25 \times 10^{10}$ protons/bunch. The bunches cross during the first 9.545 $\mu s$ of the simulation, followed by 1.5265 $\mu s$ where there is no beam, for a total revolution period of 11.0723 $\mu s$.

The beam pipe cross-section is elliptical with major radius $a = 0.047$ m and minor radius $b = 0.022$ m. We simulate $l = 0.50$ m of beam pipe in the longitudinal (beam axis) direction. We apply an external magnetic field that is primarily a dipole field with an additional quadrupole component,

$$B_x = 0.0 \tag{1}$$
$$B_y = B_0 + Gz \tag{2}$$
$$B_z = Gy, \tag{3}$$

where $B_0 = 0.1375$ T and $G = 0.3355$ T/m, $x$ is the longitudinal direction, and $y$ and $z$ are the transverse directions. We seed the simulation with a low-density, randomly distributed electron cloud. We examine the dependence of build up time and saturation density with initial seed density in section below. We use the Furman-Pivi secondary electron yield model [11] for stainless steel, with max(SEY) = 2.05 at a primary energy of $E_{\mathrm{max}} = 292.0$ eV.

* This work was performed under the auspices of the Department of Energy as part of the ComPASS SCiDAC-2 project (DE-FC02-07ER41499), and the SCiDAC-3 project (DE-SC0008920).
† veitzer@txcorp.com

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPMA037

The electrons that form electron clouds are non-relativistic, and so we perform electrostatic simulations, ignoring magnetic fields from both the beam (modeled as a time dependent charge density) and from the cloud itself. We perform the simulations with variable weight particles; splitting particles when their weights become too large, and combining them when the weights become too small. We set of target of 10,000 simulation particles at each time. Using variable weights allows us to accurately model this system where secondary emission produces a large range of numbers of particles over a single simulation. Appropriately splitting and combining the particles smoothes out the particle weights, so that a small number of highly weighted particles do not dominate the simulation. We use a biconjugate gradient method with a relative tolerance of $1.0 \times 10^{-12}$ and domain decomposed preconditioners to solve Poisson's equation on a Uniform Cartesian mesh in three dimensions with 48x16x16 cells, executed in parallel on 16 cores. We set the time step to be 8.39 ps, for 181,816 time steps.

## SIMULATION RESULTS

Figure (1) shows the total number of electrons in a typical simulation over one revolution period, on a semilog scale. Since the volume is constant, this is equivalent to the overall electron cloud density. The Three regimes; build up, saturation, and dissipation can be seen in the figure. In our simulations, the rate of build up for the PIP-II beam charge is faster, and there is a somewhat larger density at saturation. In addition, the survival rate is higher for the PIP beam.

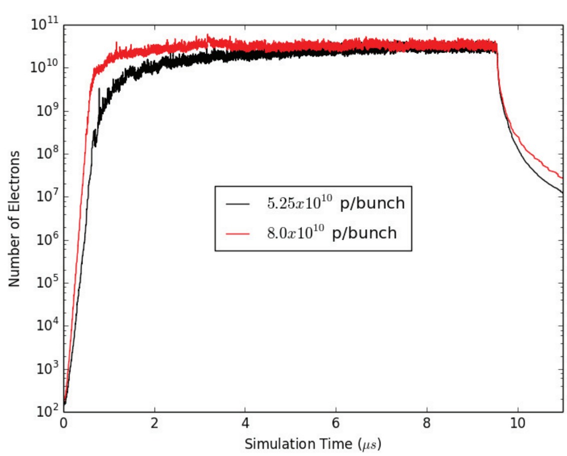


Figure 1: Total number of electrons as a function of time, showing electron cloud build up, saturation, and dissipation, for current recycler (black) and PIP-II (red) beam currents.

### *Build Up*

Figure (2) shows the build up (blue) of the cloud over the first micro-second of the simulation, and the dissipation (black) of the cloud over the last two micro-seconds. As can be seen in Figure (2), the build up phase is initially exponential for the first $0.6\mu s$ due to unabated secondary electron emission. After this the increase flattens out until space charge screening by the cloud reaches saturation. The average number of electrons at saturation is approximately $2.40 \times 10^{10} e^-$ for the lower density beam, and approximately $3.17 \times 10^{10} e^-$ for the PIP-II beam. These represent 45.7% and 39.6% of the number of protons per bunch, respectively.

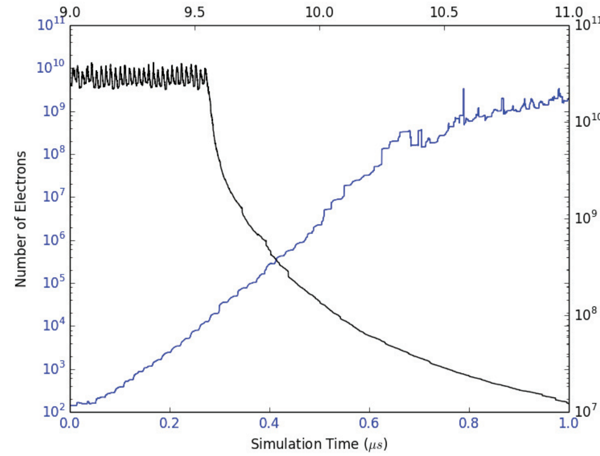


Figure 2: Detail of build up (blue) and dissipation (black) in simulation with beam density of $5.25 \times 10^{10}$ p/bunch. Note that scales on the left and bottom are for the build up plot and those on the right and top are for the dissipation plot.

Since the magnetic field is strongly directed in the vertical simulation direction, electron orbits are mostly confined to be in this direction as well.

### *Dissipation*

In the absence of crossing bunches, the number of electrons rapidly decreases from the saturation value. Since there is no longer any acceleration of the cloud electrons due to beam potentials, they drift to the beam pipe walls where they are absorbed. The energy of drifting electrons is low, below the maximum of the SEY curve, and so it is unlikely that these electrons will produce a significant amount of new secondaries. Some fraction of electrons in the cloud after the last beam bunch crosses will have energies sufficiently low enough that they will not drift to a beam pipe wall in the period of time before the beam returns on it's next revolution ($\sim 1.5\ \mu s$). These electrons will survive and seed the build up of the electron cloud over the next revolution period. In our simulations, we find a survival rate of approximately 0.05% in both cases that we modeled. This is much lower than has been recently observed in the recycler.

One may expect that secondaries that are created as a result of the last bunch to cross the simulation domain are responsible for a large portion of the surviving electrons, primarily because secondary electrons are created with low energies and at the beam pipe walls, so they have the longest distance to drift before being absorbed. Figures (3) and (4) show the number of simulation and physical (respectively) primary and secondary electrons isolated to just before the

ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-MOPMA037

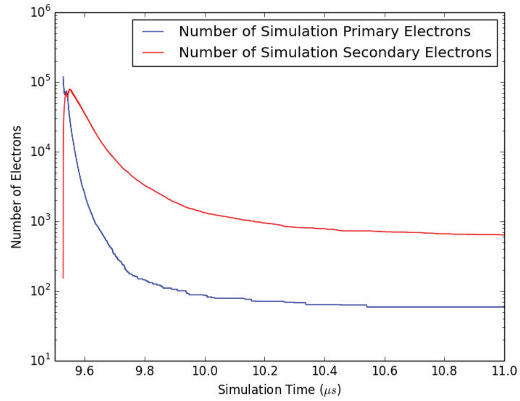


Figure 3: Number of electrons as a function of simulation time divided into primary and secondary types.

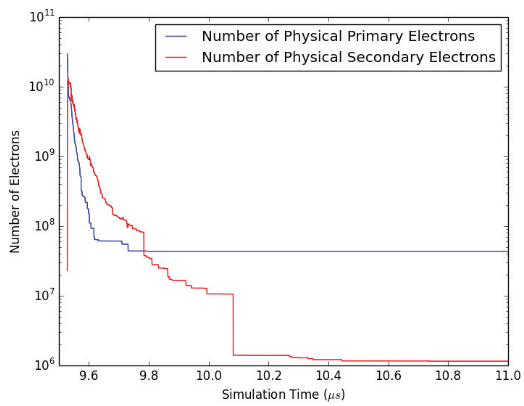


Figure 4: Number of electrons as a function of simulation time divided into primary and secondary types.

last bunch crosses the simulation domain. In this case, the number of simulation particles that survive is an order of magnitude greater for secondary electrons, while the number of physical electrons is an order of magnitude less. However, these results should be interpreted with caution, because the number of primary electrons is dominated by a single, very large weight simulation particle, that is likely skewing the survivability results. Further, higher-definition simulations are currently being done to resolve this issue.

## FUTURE WORK

The model results reported here indicate that there is likely to be at least some electron cloud that survives from beam to beam in the Recycler. This is not likely to be mitigated by increasing the percentage of time with no beam since surviving electrons have very low velocities, and hence will not be absorbed readily in-between beam crossings unless actively mitigated. One possible mechanism for *cleaning* out the electrons is to inject a trailing proton bunch with low total charge. The charge and timing of this bunch could be optimized to provide surviving electrons with enough energy to make it to the beam pipe walls before the beam returns, but not to give enough energy to put the electrons close to the peak of the SEY curve, so that they are absorbed instead of producing more secondary electrons. Determining the effectiveness of this technique is the focus of our current research.

We would like to thank and acknowledge Y. Alexahin, S. Antipov, and the other members of the FNAL ecloud task force for invaluable discussions about the FNAL program and their advice.

## REFERENCES

[1] P. Lebrun, P. G. Spentzouris, J. R. Cary, P. H. Stoltz, S. A. Veitzer, "Accurate Simulation of the Electron Cloud in the Fermilab Main Injector with Vorpal", *Proc. PAC'10*, TUPD015, (2010).

[2] P. Lebrun et al., "A Comparison and Benchmark of Two Electron Cloud Packages: POSINST and VORPAL", *FERMILAB-TM-252APC*, 2012.

[3] S.A. Veitzer, P.H. Stoltz, "Model rf Resonant Cavity Method For Measuring Electron Cloud Effect Using Plasma Dielectrics", *Proc. AAC'14*, WG2, (2014).

[4] G. Rumolo, F. Zimmermann, "Electron-cloud simulations: Buildup and related effects," *Mini Workshop on Electron Cloud Simulations for Proton and Positron Beams (ECLOUD'02)*, Geneva, Switzerland, 15-18 Apr. (2002).

[5] J.-L. Vay, C. M. Celata, M. A. Furman, G. Penn, M. Venturini, D. P. Grote, K. G. Sonnad, "Update on Electron-Cloud Simulations Using the Package WARP-POSINST", *Proc. PAC'09*, FR5RFP078, (2009).

[6] J.-L. Vay, M. A. Furman, M. Venturini, "Direct Numerical Modeling of E-Cloud Driven Instability of a Bunch Train in the CERN SPS", *Proc. PAC'11*, WEP154, (2011).

[7] S.A. Veitzer, K.G. Sonnad, P.L.G. Lebrun, P.H. Stoltz, "Modeling Electron Cloud Buildup and Microwave Diagnostics Using Vorpal", *Proc. ECLOUD'10*, MOD04, (2012).

[8] C.Y. Vallgren et. al., "Recent Experimental Results on Amorphous Carbon Coatings for Electron Cloud Mitigation", *Proc. ECLOUD'10*, OPR02, (2012).

[9] VSim, Powered by Vorpal; Empowered by Tech-X Corp.

[10] C. Nieter and J. R. Cary, "Vorpal: A versatile plasma simulation code", *J. Comput. Phys.*, **196**, pp. 448-473, (2004).

[11] M.A. Furman and M.T.F. Pivi, "Probabilistic Model For The Simulation Of Secondary Electron Emission", *PRST-AB*, **5**, 124404, (2002).
doi: http://dx.doi.org/10.1103/PhysRevSTAB.5.124404