SIMULATING ELECTRON CLOUD EVOLUTION USING MODULATED DIELECTRIC MODELS

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

Abstract

Electron clouds can pose a serious threat to accelerator performance, and understanding cloud buildup and the effectiveness of different mitigation techniques can provide cost-saving improvements in accelerator design and fabrication. Microwave diagnostics of electron clouds are a non-destructive way to measure cloud buildup, but it is very difficult to measure the cloud density from spectral signals alone. Modeling traveling-wave rf diagnostics is very hard because of the large range of spatial and temporal scales that must be resolved to simulate spectra. New numerical models have been used to generate synthetic spectra for electron clouds when the cloud density is not changing, and results have been compared to theoretical results. Here we use dielectric models to generate spectra for clouds that evolve over many bunch crossings. We first perform detailed simulations of cloud buildup using kinetic particle models, and then use an equivalent plasma dielectric model corresponding to this density, at a finer time resolution, to compute spectra. The stability and accuracy of dielectric models that spectra can be accurately determined in these very long timescale simulations.

TRAVELING WAVE RF DIAGNOSTICS MEASURE ELECTRON CLOUDS IN ACCELERATORS

Traveling-wave rf diagnostics to measure electron cloud effects in circular accelerators have been performed in a number of experiments, e.g. [1]. These methods are attractive because microwave diagnostics are non-destructive, and can be easily fielded without requiring expensive new instrumentation. In addition, microwave diagnostics are sensitive to the spatial distribution of the electrons, which in simulations show variation of side band height for different spatial distributions, but with the same overall plasma density [2]. This is a known effect in electron clouds due to different magnetic field configurations.

In traveling-wave rf experiments, plasma density is inferred from spectral data that is typically collected some meters away from the rf source. A example of this is shown in Fig. (1). A phase shift in the rf is induced by the dielectric properties of the electron plasma, and the plasma density is modulated harmonically by gaps in the bunch train, during which the electron clouds dissipate to the walls of the accelerator. This modulation appears as side bands in the spectra, and the height of the side band with respect to the carrier can be linearly related to the plasma density, under some simplifying assumptions.

\[
\epsilon = 1 - \frac{\omega_p^2}{\omega^2}
\]  

(1)

where \(\omega_p = 56.4 \sqrt{n_e}\) is the plasma frequency. For magnetized plasmas, the dielectric constant is replaced with a dielectric tensor, whose strength can be similarly related to the spectral data showing side bands induced by electron cloud plasmas in the Main Injector for two different magnetic field configurations. The height of the first side band is nominally proportional to the average cloud density in the linear approximation. Reproduced from [3].

Electron cloud buildup has previously been modeled using a variety of high-performance Particle-In-Cell (PIC) codes, including V orpal [4, 5], Warp coupled with POSINST [6, 7]. However, it is difficult to accurately model the generation of side bands numerically using Particle-In-Cell (PIC) codes because there is a separation of scales between the rf and the modulation frequencies at play here. In order to resolve the rf signal, time steps are required to be on the order of 10 - 100 ps. However, modulation of the cloud that produces the side bands is on a revolution timescale, so simulations need to cover many hundreds or thousands of \(\mu s\) in order to resolve side bands in synthetic spectra.

Recognizing that it is the dielectric properties of the electron plasma that gives rise to phase shifts in traveling wave experiments, and modulation of the plasma that produces side bands, a new simulation model for electron clouds based on plasma dielectrics was recently introduced [8, 9]. In plasma dielectric models, kinetic particles are replaced by an equivalent dielectric field, where the linear plasma dielectric strength, for an unmagnetized plasma is simply
the cloud density. In order to model side bands in plasma
dielectric simulations, the dielectric strength is harmoni-
cally modulated at the revolution frequency, as has previ-
ously been reported. However, simulations must be per-
formed over very long time scales in order to resolve side
bands in frequency space.

Plasma dielectric models have a number of advantages
over kinetic PIC models for electron clouds. First, they
are less noisy and more stable than kinetic models. Kinetic
particles produce so-called particle noise, which arise from
small errors in the interpolation of particle charges and cur-
cent to the computational grid. Particle noise can be sup-
pressed by using higher-order particle stencils or by using
more simulation particles (both at the expense of computa-
tional performance). Second, plasma dielectric models
are generally faster than the equivalent kinetic PIC mod-
els. In PIC simulation codes, particle pushes, i.e. moving
particles each time step by the electric and magnetic fields,
are computationally expensive. Similarly, interpolation of
particle charges and currents to the computational grid is
required to numerically solve Maxwell’s (electromagnet-
ics) or Poisson’s (electrostatic) equations. Plasma dielec-
tric models replace these model components with field up-
dates, on the same level as updating the electric or magnetic
field in the typical Yee algorithms, which is much faster for
each time step. There are disadvantages to using plasma di-
electric models over kinetic PIC models as well. First, the
required time steps in a plasma dielectric simulation are
limited by the Courant-Fredrichs-Lewy (CFL) [10] condi-
tion. This condition is imposed by explicit finite-difference
time-domain Yee algorithms for numerical stability. Typi-
cally, the CFL condition imposes a time step that is smaller
than the time step for electrostatic simulations. In our spe-
cific case, this difference is at least a factor of twenty. Sec-
ond, there is no way to determine the spatial evolution of
electron clouds from a plasma dielectric model. As op-
posed to kinetic PIC simulations, forces on the underlying
electron plasmas are never computed, so it is not possible
to consistently change the spatial distribution of electrons
over time.

In our current simulations, we would like to reproduce
spectra and resolve side bands for traveling wave rf diag-
nostics in the Main Injector for realistic electron clouds as
they undergo buildup and decay over many bunch trains.
In order to achieve this goal we use VSim [11] to perform de-
tailed electrostatic kinetic PIC simulations of cloud buildup
over a single revolution, and use the resulting plasma den-
sities in subsequent electromagnetic plasma dielectric sim-
ulations over many revolution periods. This paper reports
preliminary results that demonstrate the feasibility of these
simulation methods, with special attention paid to under-
standing the computational performance requirements.

**SIMULATION RESULTS**

We are developing numerical models that are appropri-
ate for simulating electron clouds and rf diagnostics in the

Main Injector at Fermilab. In all of the simulations reported
here, we use a circular cross section beam pipe with radius
7.46125 cm, and 50 cm long in the along-beam direction.
We use a mesh with 48 computational cells in the longitudi-
unal direction, and 16 cells in each of the transverse di-
rections. We simplify the bunch train structure from that in
the actual Main Injector by modeling one full revolution
as a single continuous bunch train of 18.8 ns bunches of
roughly 8 GeV protons. We artificially set one revolution
time to 2.0µs, including an abort gap of 0.4µs during
which time there are no beam bunches. This sets the modu-
lation frequency to 500 kHz. The cutoff frequency for this
beam pipe is 1.177 GHz, and we drive rf at 1.05 times the
cutoff frequency.

**Kinetic PIC Simulations**

We first perform detailed 3-Dimensional, electrostatic,
kinec PIC simulations of electron cloud buildup. Since
the simulations are electrostatic, the time step is not lim-
ited by the CFL condition, but rather need only resolve the
Debye length in the plasma. We set the time step for the
kinetic simulations to 0.3946µs, so that we well resolve
the beam bunches, although we have determined that we
get the same cloud behavior (with slightly lower resolu-
tion) with time steps up to a factor of 40 longer than this.
One revolution is only about 5,000 steps at this resolution,
and we save the electron 6D phase space every 5 time steps
to be used in the plasma dielectric simulations. Figure (2)
shows the total number of electrons in our simulations as a
function of time for one revolution period. Initially there is
a slow, but exponential increase in the number of electrons,
followed by a period of saturation, where the proton beam
potential is screened by the electron cloud. Finally, dur-
ing the abort gap, the cloud dissipates to the walls and the
density drops off accordingly. The average cloud density at
saturation is approximately 1.83 × 10^{12} electrons/m^3.

**Plasma Dielectric Simulations**

The cutoff frequency in our simulations is 1.177 GHz,
and we drive rf at 5% above this value, or at a frequency of
1.236 GHz. The plasma dielectric strength is modulated at
500 kHz, and we simulate 10,000 rf periods. Our plasma
dielectric simulations are electromagnetic in nature, so the
time step is limited by the CFL condition. For our modest
grid size (48x16x16), the time step is 18.86 ps, giving ap-
proximately 10.6 million time steps per simulation. First
we have performed simulations where the plasma dielec-
tric is spatially uniform, with a strength that is equivalent
to the saturation density of the plasma from buildup simula-
tions, and that is harmonically modulated at the modulation
frequency. This is primarily for verification of the modu-
lated plasma dielectric methods, but also for comparison
with simulations for which plasma densities determined by
buildup simulations are used. Figure (3(top)) shows the
spectra for this case. Higher-order side bands can be seen
in the figure. However, longer simulations are needed to re-

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solve the first-order side band because it is only separated from the carrier by one half of one percent.

REFERENCES


