

MODELING ELECTRON CLOUD BUILDUP AND MICROWAVE DIAGNOSTICS USING VORPAL *

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Abstract

Electron cloud effect may seriously limit future accelerator performance when electron plasmas build up enough to cause instabilities in beams. Detailed simulations of electron cloud buildup, effects on beams, and mitigation will increase future accelerator performance and provide aid in the effective design of future accelerators. We present results of recent VORPAL simulations directed at modeling of microwave diagnostic experiments for measuring electron cloud effect. We focus on the effects of spatial non-uniformity of electron clouds on phase shift measurements and on directly correlating observed side-band amplitudes with cloud density.

SIMULATION OF ELECTRON CLOUDS ENHANCES ACCELERATOR PERFORMANCE

VORPAL

The VORPAL [1] code, a 3D finite-difference time-domain (FDTD) electromagnetics code, is designed for massively parallel distributed computing as well as for running in serial on desktop computers. Domain decomposition, a technique in which a large computational physical domain is split up into smaller pieces, which are then distributed on many different processes, is a powerful method for parallel computing, and is used extensively in VORPAL in order to improved computational performance and enable researchers to address very large simulation problems with short time scale resolution. VORPAL is appropriate for simulating traveling-wave diagnostics of electron clouds, both because it has the ability to span large spatial scales (determined by the system geometry) as well as short time scales (determined by the frequency of the rf and the spatial resolution), and because it can capture 3-Dimensional effects, such as the role of quadrupole magnets on electron density profiles. VORPAL also includes full models for complex electromagnetic-particle-boundary interactions, including embedded cut-cell geom-

etry (2nd order accurate for the calculation of EM fields), self-consistent EM fields, including the effects of space charge, secondary electron emission, and self-consistent kinetic particle motion.

Figure (1) shows a typical VORPAL simulation layout. The beam pipe can be constructed with different cross-sections, such as circular, elliptical, or rectangular, depending on the system being modeled. The ends of the simulation domain contain Matched Amplitude Layers (MALs) or Perfectly Matched Layers (PMLs) which absorb EM waves and damp them out so that there are not numerical reflections off the end of the simulation domain. The electron cloud is represented by kinetic particles which evolve under the influence of electric and magnetic fields from various sources, such as a simulated rf signal traveling down the beam pipe, a beam current, externally defined magnetic fields, and space charge. Typically, an artificial current density at one end of the simulation, oscillating at the rf frequency, is added to generate a traveling rf signal, which passes through the electron cloud and can be measured on the other side. Phase shifts induced in this rf signal can be measured by comparing simulations with and without an electron cloud. In addition, long time-scale simulations to address electron cloud buildup under different conditions (external magnetic field configurations, secondary electron yield profiles, simulation geometry) have been carried out using a similar simulation setup, and are reported elsewhere [2].

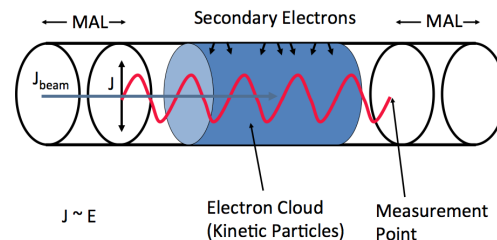


Figure 1: Typical diagram of a VORPAL electron cloud and microwave diagnostic simulation.

Simulation of Traveling Wave rf Diagnostics

In the simulation setup described above, traveling rf waves are emitted from the source current in both directions. The backward-propagating wave is almost immediately absorbed by the MAL or PML which is speci-

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cally placed at the ends of the simulation region to absorb the waves without significant reflections. The forward-propagating wave travels through the electron cloud and is absorbed by a MAL or PML on the other end of the simulation. Measurement of the wave amplitude and phase is done just upstream of the absorbing layer. Phase shifts due to an electron cloud can be measured by conducting two simulations, one with electrons and one without, and then directly comparing the two resulting time series' using simple trigonometric expansions.

For uniform density clouds, theory predicts that the phase shift per unit length is

$$\frac{\Delta\Phi}{\Delta L} = \frac{\omega_p^2}{2c(\omega^2 - \omega_c^2)^{1/2}} \quad (1)$$

where ω is the rf frequency, ω_c is the cutoff frequency, and $\omega_p = \sqrt{n_e e^2 / \epsilon_0 m_e}$ is the plasma frequency. Simulations for uniform density clouds [3] agree well with the linear theory, as is shown in Fig. (2).

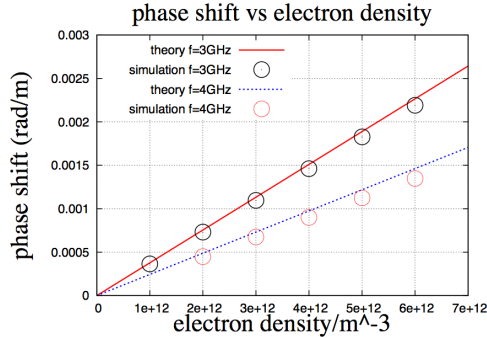


Figure 2: Phase shift against cloud density for uniformly distributed clouds. Simulated phase shifts correspond well with linear theoretical predictions. Figure reproduced from [3].

Cyclotron resonances have also been measured using VORPAL simulations with a similar setup, but with an additional externally applied magnetic field. A transversely directed dipole magnetic field will excite an upper-hybrid resonance if the applied field is normal to the rf electric field. Since the plasma density is low, the cyclotron frequency is nearly the same as the upper hybrid frequency, and is given by

$$\omega_{uh} \approx \omega_{ce} = \frac{qB}{m_e c} \quad (2)$$

Researchers [4] have simulated the cyclotron resonance using VORPAL by performing simulations of the transmission of TE₁₁ and TM₀₁ waves through cold electron clouds with externally applied dipole fields that are oriented in different directions and with different strengths. Figure (3) shows a comparison of these simulations for TE₁₁ waves with an experimental measurement made at the PEP II facility [5].

Oral Session

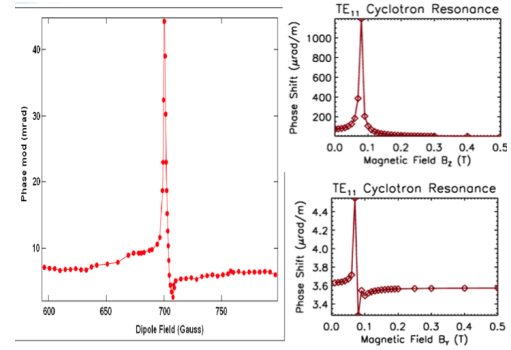


Figure 3: Cyclotron resonance in electron cloud-induced phase shifts. The left hand plot is reproduced from [5], from an experiment on the positron ring of PEP-II. The right hand plots show simulated phase shifts measured when the magnetic field is normal to the rf electric field (B_z) and parallel to the rf electric field direction (B_y). Small shifts in the second case are due to discretization errors in the simulation, and are on the order of 0.4%.

NON-UNIFORM DENSITY CLOUDS AND CONSEQUENCES FOR TRAVELING WAVE EXPERIMENTS

Theoretical models for phase shifts induced by electron clouds in traveling rf experiments typically assume that the clouds themselves are spatially uniform. However, cloud density evolves and grows as bunches accelerate electrons to the beam pipe walls, creating secondary electrons, and clouds typically disappear on a beam revolution time scale as gaps in the bunch train provide enough time for the cloud to relax and electrons to be reabsorbed. Even when averaged over a bunch-crossing or revolution time scale, the spatial distribution of electrons in a cloud is not necessarily uniform, as is demonstrated in Figure (4). The figure shows integrated cross sections of particle positions for four different magnetic field configurations and three different times in VORPAL simulations in an elliptical beam pipe section (Main Injector). The first column represents the time of first bunch crossing, 17 ns into the simulation. The middle and right-hand columns are snapshots of electron distributions at 500 ns and 1000 ns respectively. The top row in the figure corresponds to a simulation with no applied magnetic field, and the oscillating effect of bunch crossings can be seen. The second row shows that a modest solenoidal field (10 G in this case) can be effective in confining secondary electrons close to the beam pipe walls. However, the third row shows that an additional small transverse dipole field (10 G in the vertical direction here) negates the effect of the solenoidal field. Finally, the bottom row shows that a very non-uniform banded structure appears when a significant dipole field is attached. In this case a 2350 G vertical dipole field is applied to the simulations. Note that the cross section is elliptical in these simulations, with an aspect ratio of nearly 2:1, which ex-

plains the increased density near the top and bottom poles in some of the plots.

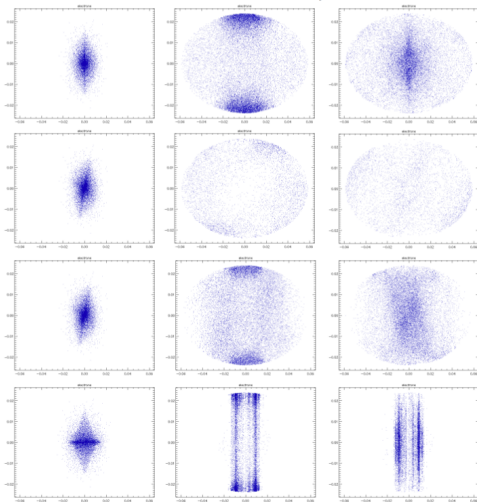


Figure 4: Non-uniformity in electron cloud distributions depends on the magnetic field configuration. A comparison of different VORPAL simulations at 17 ns, 500 ns, and 1000 ns (columns 1, 2, and 3 respectively). Magnetic configurations are (top) no external fields, (second row) 10 G solenoidal field out of the plane, (third row) 10 G solenoidal and vertical dipole fields, and (bottom) 2350 G vertical dipole field.

Experimental determination of electron cloud densities using traveling wave rf diagnostics do not directly measure phase shifts such as can be done in simulations. Typically traveling wave experiments will observe side bands at multiples of the beam revolution frequency because over long time scales the electron cloud is modulated because gaps in the bunch train allow sufficient time for the cloud to relax and the electrons to be absorbed into the beam pipe walls. The amplitude of observed side bands depends on the cloud density, and as such the ratio of the side band amplitude to the carrier amplitude is a good relative measurement of the cloud density. However, it is very difficult to deduce absolute density from side band measurements, because the theoretical treatment for traveling wave rf diagnostics assumes uniform density clouds.

Inasmuch as phase shifts are relatively larger in spatial locations where the transverse electric field of the rf are big, it may be possible to use higher order rf modes to characterize non-uniformity in electron cloud densities. For example, the lowest order mode and circular cross section beam pipe, TE_{11} , has oscillates with a spatial pattern that has a large transverse E component around the center of the beam pipe, as is depicted in figure (5). The direction of propagation here is the X-direction, so large electric field components in the Y and Z directions indicated a TE mode.

To test whether higher order modes can measure non-uniformity in electron clouds, we performed a large number of numerical experiments with different rf modes, and

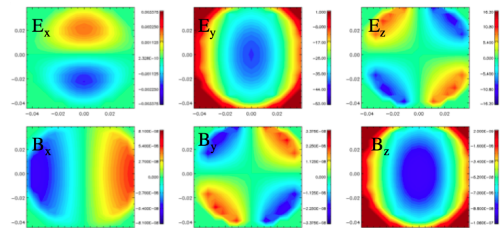


Figure 5: Electromagnetic field components for a TE_{11} in a circular cross section beam pipe.

computed phase shifts for different non-uniform cloud densities. To do this, we arranged electrons in concentric rings, as is depicted in figure (6).

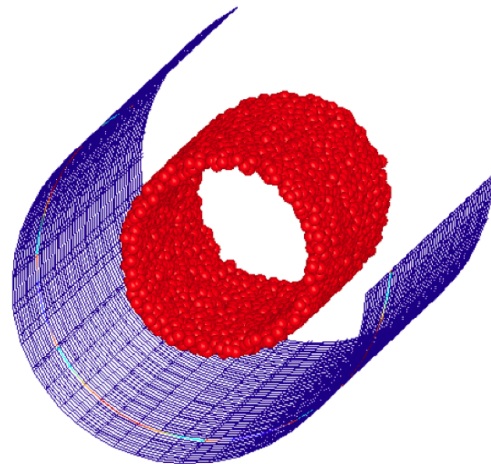


Figure 6: Typical simulation design for measuring electron cloud nonuniformity using phase shifts induced in higher order modes.

We then propagated higher order modes through the rings of electrons and computed the phase shifts using techniques described above. The results are shown in figure (7). In the figure, the phase shifts are plotted against the radius of the ring of electrons that makes up the cloud. Phase shifts do show a strong dependence on the location of the electron cloud, and in addition, the phase shift for a given cloud radius depends on the rf mode in a way that reflects the spatial pattern of the rf electric field. This analysis suggests that it might be possible to use simultaneous injection of multiple modes, both TE and TM, to measure non-uniformity in cloud density. However, there are technical obstacles to this related to power transmission and detection of higher order modes. In addition, experiments with higher order modes are likely to exhibit greater rf attenuation due to the higher frequencies involved. This is also problematic because amplitude modulation, and the loss of rf power to lower-frequency modes in not distinguishable from phase modulation.

The bottom-right plot in figure (7) is an analysis of the phase shifts for a TE_{13} mode, where the electrons in the right have a Gaussian profile, rather than being uniformly

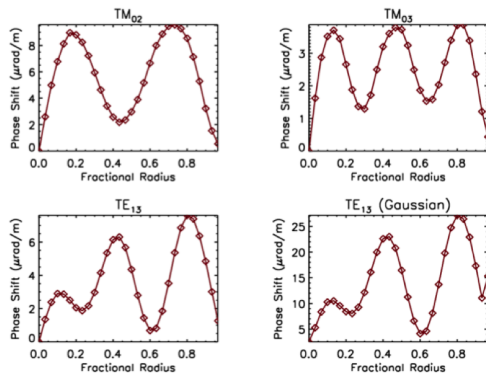


Figure 7: Higher-order mode phase shifts induced in non-uniform electron clouds as a function of radial location of the electron cloud rings.

distributed, but with the same average electron density over the ring. Comparison with the bottom-left plot shows that the exact form of the cloud is not important, but rather the radial location of cloud is the dominant factor in determining the phase shift for higher order modes.

DETERMINATION OF CLOUD DENSITY FROM SIDE BAND MEASUREMENTS

The deduction of electron cloud densities from traveling wave sideband measurements is difficult experimentally. There are a number of reasons for this, including (1) Theoretical considerations assume that the average cloud density is uniform, (2) Reflections of rf and other structural effects in the beam pipe means that the path length of the rf, and thus the amount of cloud sampled by the rf, is not accurately known, (3) amplitude modulation and loss of transmitted power is not distinguishable from phase modulation.

Straightforward time-domain simulation of electron cloud modulation is also difficult. In order to resolve side bands at the beam revolution frequency, overall simulation time needs to be at least on the order of a revolution period. However, this time scale is very long compared to a typical simulation time step, which needs to be small enough to resolve the rf wave. For instance, to achieve 10 kHz resolution, at least $200\mu\text{s}$ of overall simulation time is needed. With a 1 ps time step, needed to resolve a ~ 2 GHz rf signal, requires 2×10^8 time steps. In addition to long simulation times, numerical inaccuracies may cause problems with such long simulation times.

One possible solution to this problem is to modulate the electron weights in simulations at the revolution frequency, which will allow for the reconstruction of the spectra and associated side bands with much shorter simulation times. An example of this method is shown in figure (8). Three different cloud shapes were considered, and the particle weights were harmonically modulated at 10% of the carrier frequency (1.6 GHz). Thus side bands are observed

at intervals of 160MHz from the carrier, as can be seen in the figure. As expected, the round and rectangular clouds showed about the same side band amplitude, while the striped cloud had a significantly lower side band amplitude. This is due to the non-uniformity effects described earlier, where the rf signal interacts with the cloud primarily where the transverse electric field of the rf is greatest.

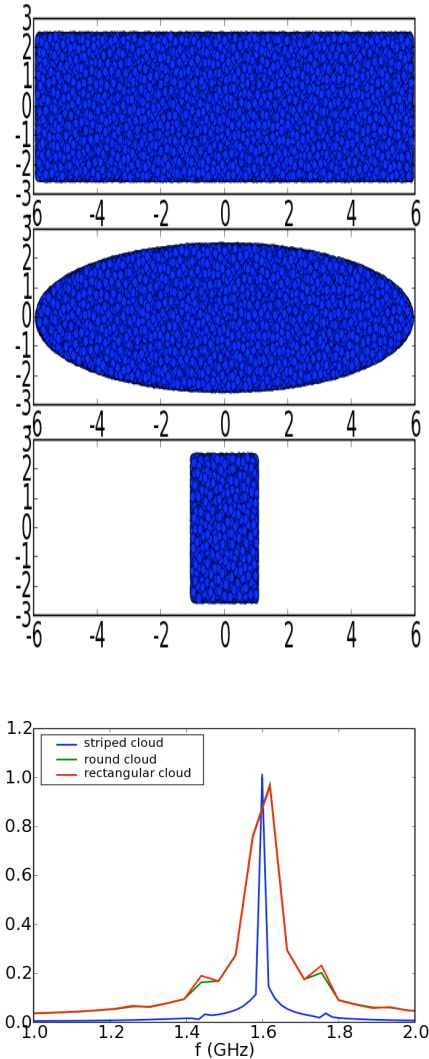


Figure 8: Simulated Fourier spectra for three different electron cloud shapes using explicit particle weighting modulation.

While the method of harmonic modulation of particle weights can reduce simulation times, the simulations are still subject to numerical instabilities due to grid heating for longer simulation times. A solution to this numerical problem is to replace simulation particles with an equivalent plasma dielectric substance. Since it is the dielectric properties of the electron plasma that induces phase shifts, a linear plasma dielectric model for the electrons can be used to effectively model traveling TE wave diagnostics.

The advantage to a plasma dielectric model is that one can avoid doing particle pushes altogether, which is generally the most time consuming part of a simulation. Thus simulations can be done which only involve field updates. The disadvantage is that buildup of the electron cloud can not be modeled with dielectrics alone. Also, external magnetic fields complicate the model somewhat, requiring a dielectric tensor instead of a scalar dielectric constant. Also, the linear assumption will break down at plasma densities above about $1.0e^{17}$ for these types of simulations. However, typical electron cloud densities are several orders of magnitude below this value. This advanced model is currently being developed [6], and will provide both greater numerical stability for long simulations, as well as improving the performance of the simulations.

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