SIMULATING ELECTRON CLOUD EVOLUTION USING MODULATED DIELECTRIC MODELS*

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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.

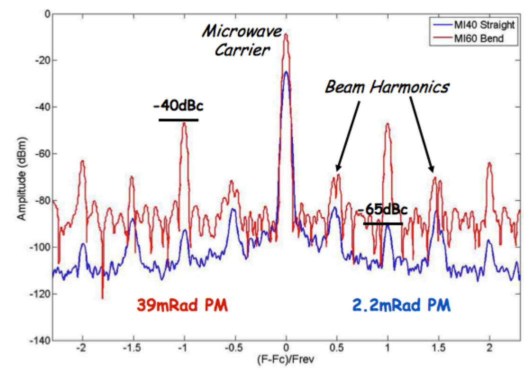

Figure 1: Spectral data showing side bands induced by electron cloud plasmas in the Main Injector for two different magnetic field configurations. The height of the first side band is nominally proportional to the average cloud density in the linear approximation. Reproduced from [3].

Electron cloud buildup has previously been modeled using a variety of high-performance Particle-In-Cell (PIC) codes, including Vorpal [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 μs 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

$$\epsilon = 1 - \frac{\omega_p^2}{\omega^2} \quad (1)$$

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

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the cloud density. In order to model side bands in plasma dielectric simulations, the dielectric strength is harmonically modulated at the revolution frequency, as has previously been reported. However, simulations must be performed 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 current to the computational grid. Particle noise can be suppressed by using higher-order particle stencils or by using more simulation particles (both at the expense of computational performance). Second, plasma dielectric models are generally faster than the equivalent kinetic PIC models. 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 (electromagnetics) or Poisson's (electrostatic) equations. Plasma dielectric models replace these model components with field updates, 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 dielectric 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] condition. This condition is imposed by explicit finite-difference time-domain Yee algorithms for numerical stability. Typically, the CFL condition imposes a time step that is smaller than the time step for electrostatic simulations. In our specific case, this difference is at least a factor of twenty. Second, there is no way to determine the spatial evolution of electron clouds from a plasma dielectric model. As opposed 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 diagnostics 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 detailed electrostatic kinetic PIC simulations of cloud buildup over a single revolution, and use the resulting plasma densities in subsequent electromagnetic plasma dielectric simulations over many revolution periods. This paper reports preliminary results that demonstrate the feasibility of these simulation methods, with special attention paid to understanding the computational performance requirements.

SIMULATION RESULTS

We are developing numerical models that are appropriate 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 longitudinal direction, and 16 cells in each of the transverse directions. 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 $2.0\mu s$, including an abort gap of $0.4\mu s$ during which time there are no beam bunches. This sets the modulation 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, kinetic PIC simulations of electron cloud buildup. Since the simulations are electrostatic, the time step is not limited 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 $0.3946ns$, so that we well resolve the beam bunches, although we have determined that we get the same cloud behavior (with slightly lower resolution) 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, during 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 approximately 10.6 million time steps per simulation. First we have performed simulations where the plasma dielectric is spatially uniform, with a strength that is equivalent to the saturation density of the plasma from buildup simulations, and that is harmonically modulated at the modulation frequency. This is primarily for verification of the modulated 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-

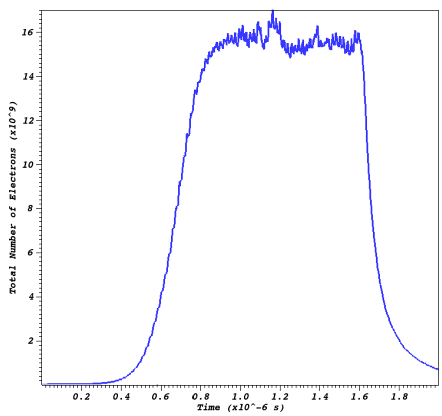

Figure 2: Total number of electrons as a function of time, showing electron cloud buildup and dissipation. Kinetic simulation results are used in our plasma dielectric simulations to set the dielectric strength.

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

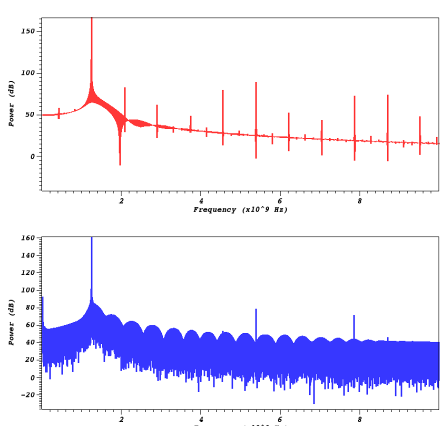

Figure 3: (top) Synthetic spectra generated by harmonic modulation of a spatially uniform plasma dielectric at the revolution frequency. (bottom) Synthetic spectra generated by translating cloud densities.

Figure (3(bottom)) shows a spectrum generated by converting electron cloud densities from the kinetic simulations into a 3-Dimensional field of dielectric strength over a single revolution period, and then repeating that pattern in a plasma dielectric simulation over 10,000 rf periods. The average density for these simulations is the same as the harmonically modulated plasma dielectric simulations, as well as the modulation frequency. However the modulation shape (in time) of the equivalent dielectric is different, being more like a square wave in these simulations as opposed to a purely harmonic variation in the previous simulations. It is expected that different fill patterns and modulation shape will affect the amplitudes of the side bands, as well as changing the power in higher-order side bands with respect to the first side band [12]. However, as can be seen in Figure (3(bottom)), the side band amplitudes are suppressed in comparison to the harmonic modulation simulations. We attribute this to the spatial distribution of electrons being highly non-uniform. In the buildup simulations, electrons tend to congregate near the beam pipe walls; only occupying regions near the beam when they are accelerated through the region by the beam potential. We expect that phase shifts induced in the rf due to plasma near the wall is less than plasma in the center of the beam pipe because TE waves have a large transverse component in the center.

REFERENCES

[1] S. De Santis, J. M. Byrd, F. Caspers, A. Krasnykh, T. Kroyer, M. T. F. Pivi, and K.G. Sonnad, "Measurement of electron clouds in large accelerators by microwave dispersion", *Phys. Rev. Lett.*, **100**, 094801 (2008).

[2] S. A. Veitzer, P. H. Stoltz, D. N. Smithe, "Advanced Modeling of TE Microwave Diagnostics of Electron Clouds", *Proc. PAC'11*, WEP165, (2011).

[3] N. Eddy, *Project X Collaboration Meeting*, 2009.

[4] 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).

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

[6] 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).

[7] M. A. Furman, "Electron-Cloud Buildup: Theory and Data", *Proc. ECLOUD'10*, in press, CBP-872/LBNL-4504E.

[8] S. A. Veitzer, H. Stoltz, J. A. Crittenden, K. G. Sonnad, "3-Dimensional Modeling of Electron Clouds in Non-Uniform Magnetic Fields", *Proc. IPAC'12*, TUOAA01, (2012).

[9] S. A. Veitzer, D. N. Smithe, P. H. Stoltz, "Application of New Simulation Algorithms for Modeling rf Diagnostics of Electron Clouds", *Proc. Advanced Accelerator Concepts Workshop*, (2012).

[10] R. Courant, K. Fredrichs, H. Lewy, "Über die partiellen Differenzengleichungen der mathematischen Physik", *Mathematische Annalen/Zeitschriftenband*, Artikel 32-74, (in german), (1928).

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

[12] S. De Santis, J. Sikora, M. Billing, M. Palmer, B. Carlson, "TE Wave Measurements of the Electron Cloud in the CESR-TA Ring", *Proc. IPAC'10*, MOPE088, (2010).

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