INTEGRATED KINETIC AND PLASMA DIELECTRIC MODELS OF ELECTRON CLOUD BUILDUP AND TE WAVE TRANSMISSION *

S. A. Veitzer†, Tech-X Corporation, Boulder, CO, 80303 USA
P. H. Stoltz, Tech-X Corporation, Boulder, CO, 80303 USA
P. G. Lebrun, Fermilab, Batavia, IL, 60510 USA

Abstract

Buildup of electron plasmas in accelerator cavities poses a serious threat to performance for current and future accelerators. Traveling-wave rf diagnostics are an effective, non-destructive way to measure electron clouds, although determining the true cloud density from spectra is difficult due to the effects of reflections, non-uniform cloud density, and magnetic field effects. We model traveling-wave rf diagnostics of electron clouds by simulating spectra using both harmonically modulated plasma dielectric models, and dielectric models based on simulated electron cloud densities. We compare here the differences in computed side band spectra due to different magnetic field configurations for Main Injector parameters, and report on computational challenges inherent to numerical modeling of systems with large variances of spatial and temporal scales.

RF DIAGNOSTICS PROVIDE DIAGNOSTIC MEASUREMENT OF ELECTRON CLOUDS

Electron clouds have been identified as a potential performance-limiting element in both hadron and lepton accelerators [1]. Recently, methods for measuring electron cloud densities in a non-destructive manner have been developed. These methods rely on measurement of rf signals injected into the beam pipe, either at a frequency just below the cutoff frequency (resonant rf method) or above the cutoff frequency (traveling wave method). For traveling wave rf diagnostics, the presence of an electron cloud plasma in the beam pipe induces a phase shift due to changes in the dielectric properties of the medium in which the rf is traveling. The plasma dielectric strength is modulated at the revolution frequency as the plasma builds up during bunch passages, and dissipates during gaps in the bunch train. This is typically observed in experiments as side bands at the revolution frequency, with a height that is proportional (in the linear approximation) to the average plasma density. Magnetic field effects also come into play with these diagnostics in two ways. First, magnetic fields may excite a cyclotron resonance [2, 3] that increases the phase delay per unit length, and second, magnetic fields will affect the electron trajectories that will in turn change the spatial distribution of electrons in the beam pipe and hence the dielectric properties of the plasma. It has been observed in both experiments and in simulations that dipole fields tend to align electrons in vertical stripes [4, 5]. Recent studies indicate that quadrupole fields may be able to trap electron clouds thereby leading to negative effects on the lead bunch in a train [6].

* 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

SIMULATION RESULTS

We are developing numerical models that are appropriate for simulating electron clouds and rf diagnostics in the Main Injector at Fermilab, using the plasma simulation framework VSim [7]. In all of the simulations reported here, we use a circular cross section beam pipe with radius 7.46125 cm, and 50 cm long. 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 0.4μ 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 1.1774 GHz, and we drive rf above this frequency to model traveling wave diagnostics.

Kinetic PIC Simulations

We first perform detailed electrostatic Particle-In-Cell (PIC) simulations of electron cloud buildup using VSim. We start with a low-density, uniformly distributed, cold electron plasma in a circular beam pipe with radius 7.46 cm. We solve for the electric fields electrostatically given the overall charge distribution and subject to the appropriate boundary conditions; metallic boundaries on the beam pipe walls, and port boundaries on the open ends of the simulation domain. Port boundaries are a numerical filter model that effectively absorbs wave energy at a given phase velocity, preventing reflections from the boundary. We do not inject rf power in the kinetic simulations because we are focused on modeling cloud buildup here.

In buildup simulations we inject beam bunches with a spacing of 18.8 ns by specifying a time-dependent charge density that simulates the passage of proton beam bunches. Bunches cross the simulation domain for 1.2μs, followed by a 0.8μs abort gap, representing a single revolution. These times are chosen to demonstrate the physics of electron cloud buildup while maintaining numerical efficiency. In future simulations the actual Main Injector revolution period will be approached. Electrons that make up the plasma (cloud) are modeled as variable-weight kinetic par-

ISBN 978-3-95450-138-0

ticles, and are pushed by electrostatic forces from other charges (space charge effects) and current sources (beam potential). Electrons are attracted to the potential of the beam as it passes and are accelerated across the beam pipe into the opposing wall. Electrons that are absorbed by the beam pipe walls emit low-energy secondary electrons according to the Furman-Pivi model [8]. These electrons are accelerated by subsequent bunches giving rise to a buildup of electrons, that saturates at a density that is about 0.7 times the linear beam density [9], where the cloud shields electrons from the beam potential.

In our buildup simulations we set the time step to be 18.86 ps in order to match the plasma dielectric simulations whose time steps are limited for numerical stability reasons (CFL condition), although we could relax this by a factor of at least 20 and just resolve the Debye length because these simulations are electrostatic. We save the 6D phase space for each particle at each time step. We then compute the charge density for the electron cloud from the particle positions and can subsequently use that density in plasma dielectric simulations over many revolution periods (see below).

Figure 1 shows the total energy of the cloud electrons as they build up. On average the energy follows the total number of electrons in the buildup and dissipation of the cloud. The inset shows fine-scale structure indicating bunch crossings. Spikes in the electron energy are due to a single bunch crossing, where the electrons are accelerated by the positively-charged bunch. Nearly all of this energy is lost when the (fast) electrons are absorbed by the walls. There is a short period of drift, capped off with a period where some (slow) electrons are absorbed by the walls that creates a reduction in the total energy that corresponds to a reduction in the total number of electrons.

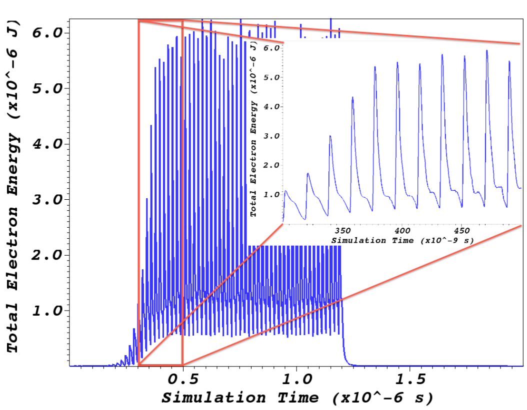

Figure 1: Total energy of the electron cloud as a function of simulation time. Bunch crossings punctuate the electron energy, which then relaxes as electrons are absorbed by the beam pipe walls.

Modulated Plasma Dielectric Simulations

We modulate the dielectric strength at a frequency of 500 kHz to match the kinetic buildup simulations, and simulate approximately 160 revolution periods with a time step of 18.86 ps, or approximately 16.78 million time steps. This corresponds to at least 550,000 rf periods, which is sufficient to resolve plasma-induced side bands. We use port boundaries to launch an rf wave into the simulation from the left boundary. This rf wave is then measured at the right end of the simulation after it has passed through the plasma dielectric.

In these simulations we model rf propagation through a plasma dielectric that is spatially uniform across the whole simulation domain, with an equivalent plasma density of 9.1×10^{12} electrons/m^3, corresponding to 8.0×10^{10} electrons at saturation during buildup in our kinetic PIC simulations. The dielectric tensor is modulated purely harmonically at 500 kHz, simulating the effects of dissipation of the cloud during gaps in the bunch train. Simulations such as these are much smoother than simulations where the plasma density at each time step is determined by particle positions from kinetic PIC simulations. They also serve to demonstrate the modeling capability of accurately generating synthetic spectra with side band structures, that can be directly compared to experimental results, and require numerical stability and accuracy over extremely long simulation times.

Figure 2 shows a portion of the synthetic spectrum for uniform, modulated plasma dielectric simulations. The left-hand plot shows the spectrum for a simulation run with rf at 50% above the cutoff frequency with no externally applied magnetic fields, and the right-hand plot is for a simulation driven at 5% above cutoff with a 0.06 T transverse dipole applied field, which is close to the cyclotron resonance. The spectrum is very smooth because the simulations plasma dielectric is spatially uniform, and the simulations are run for a long time which gives better frequency resolution. The first side band is readily seen at the modulation frequency and the height of the side band is dependent on the plasma dielectric constant, as expected.

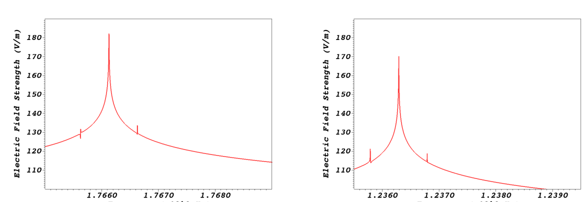

Figure 2: Synthetic spectra generated by harmonic modulation of plasma dielectric tensor. Left plot shows the spectrum with zero applied magnetic field, driven at 50% above the cutoff frequency. Right plot shows the spectrum with excitation of the extraordinary wave, near the cyclotron resonance with an applied dipole field of 0.06 T, and hence the upper hybrid resonance, driven at 5% above the cutoff frequency.

ISBN 978-3-95450-138-0

The effect of externally applied magnetic fields on plasma-induced phase shifts in rf diagnostics has been documented [4, 5, 10]. Here we have performed simulations with different magnetic field orientations using the modulated plasma dielectric model. In Figure 2, the left-hand plot shows the spectrum for the case where there is zero magnetic field, as in a drift section. The right-hand plot shows the spectrum in the case where there is an applied dipole magnetic field with strength 0.06 T oriented in the transverse direction normal to the rf polarization. This orientation excites the upper hybrid resonance which modifies the side band strength. All other simulation parameters are the same between these simulations. Simulations in which an applied magnetic field is aligned parallel to the rf polarization do not show any enhancement in the side band strength.

Integrated Plasma Dielectric Simulations

For these simulations we implement a plasma dielectric model based on electron cloud densities derived from the kinetic simulations described above. For integrated plasma dielectric simulations we first convert particle positions from the buildup simulations into a 3-Dimensional density map that we use as input to our plasma dielectric model. We then perform plasma dielectric simulations for nearly 200 revolutions, changing the value of the dielectric tensor in each computational cell periodically according to the electron density in that cell. We repeat the electron densities determined in the corresponding kinetic buildup simulations every $2.0\mu s$, and sub-sample the electron positions, changing the corresponding plasma dielectric strength every 50 time steps for computational efficiency. We drive the rf at 2.2 times cutoff in these simulations.

Figure 3 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 1,000,000 rf periods. The average density for these simulations is the same as the harmonically modulated plasma dielectric simulations discussed above. It may be 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 [11]. As can be seen in Figure (3), the first side band amplitude is somewhat larger in comparison to the harmonic modulation simulations. In addition, higher order side bands are observed, as is expected because the shape of the modulation of the electron density is more like a square wave than a purely harmonic signal. The spectrum overall is much coarser than the previous simulations, and there is more high-frequency noise. This is due to the discreteness of both the binning of electron positions to the computational grid, as well as undersampling effects.

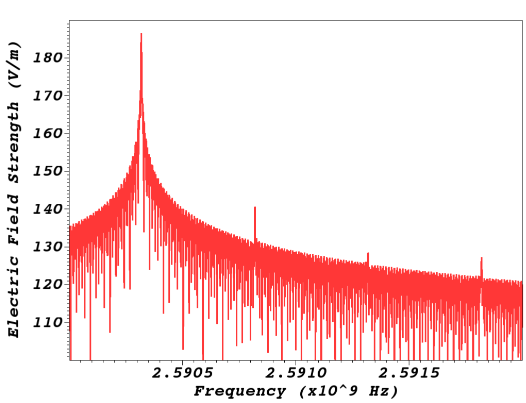

Figure 3: Simulated spectrum for integrated plasma dielectric model, where the 3-Dimensional electron densities from kinetic simulations determines the plasma dielectric strength.

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