# Modeling Electron Cloud Buildup and Microwave Diagnostics Using VORPAL

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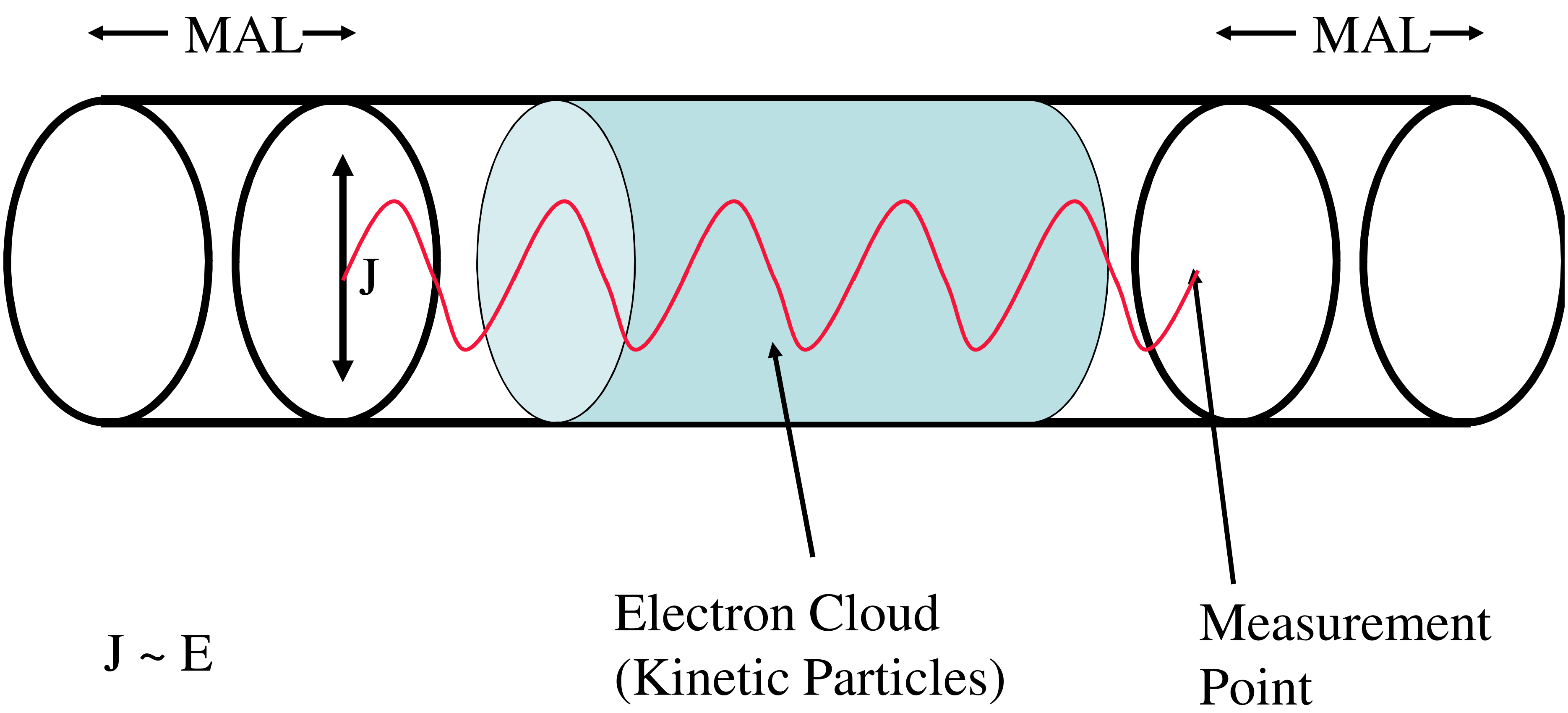
# New Simulation Models Help Us Understand Electron Cloud Effects

- Electron cloud effect may seriously limit future accelerator performance
- Simulations of electron cloud effects will increase performance and aid in the design of future high-current accelerators
- Recent simulations using VORPAL have focused on two main difficulties in microwave diagnostics for measureing electron clouds
- 1. Electron clouds are spatially non-uniform
- 2. Direct correlation between sideband amplitude measurements and electron cloud density is difficult
- VORPAL is a 3-Dimensional PIC, self-consistent, plasma simulation code that runs on laptops up to leadership class high-performance clusters
- VORPAL is appropriate for simulating microwave diagnostics as well as complex particle-boundary interactions
- These electrodynamic simulations include embedded cut-cell geometry, self-consistent EM fields, kinetic particles, and secondary electron emission

# VORPAL Simulations

•Simulation geometry




J ~ E

# VORPAL Simulations

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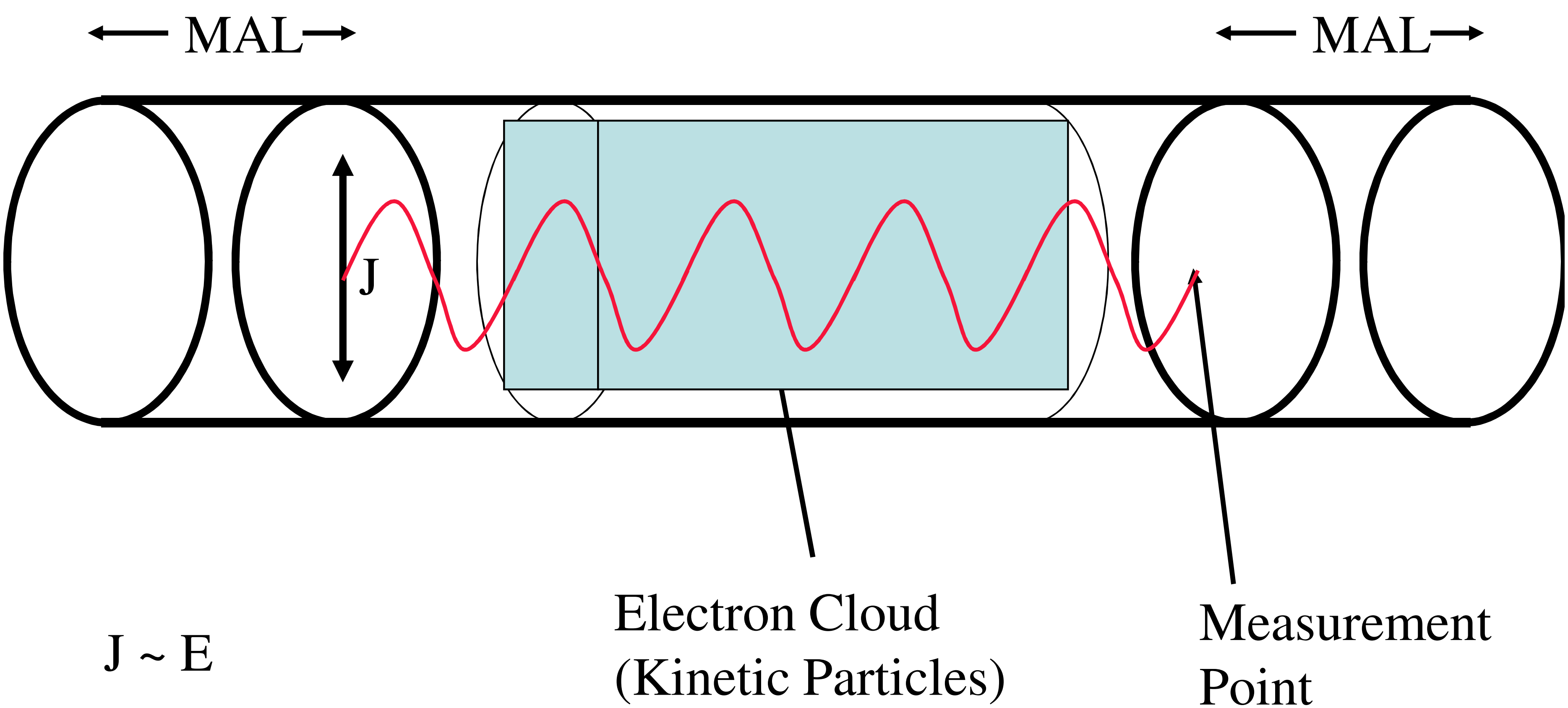

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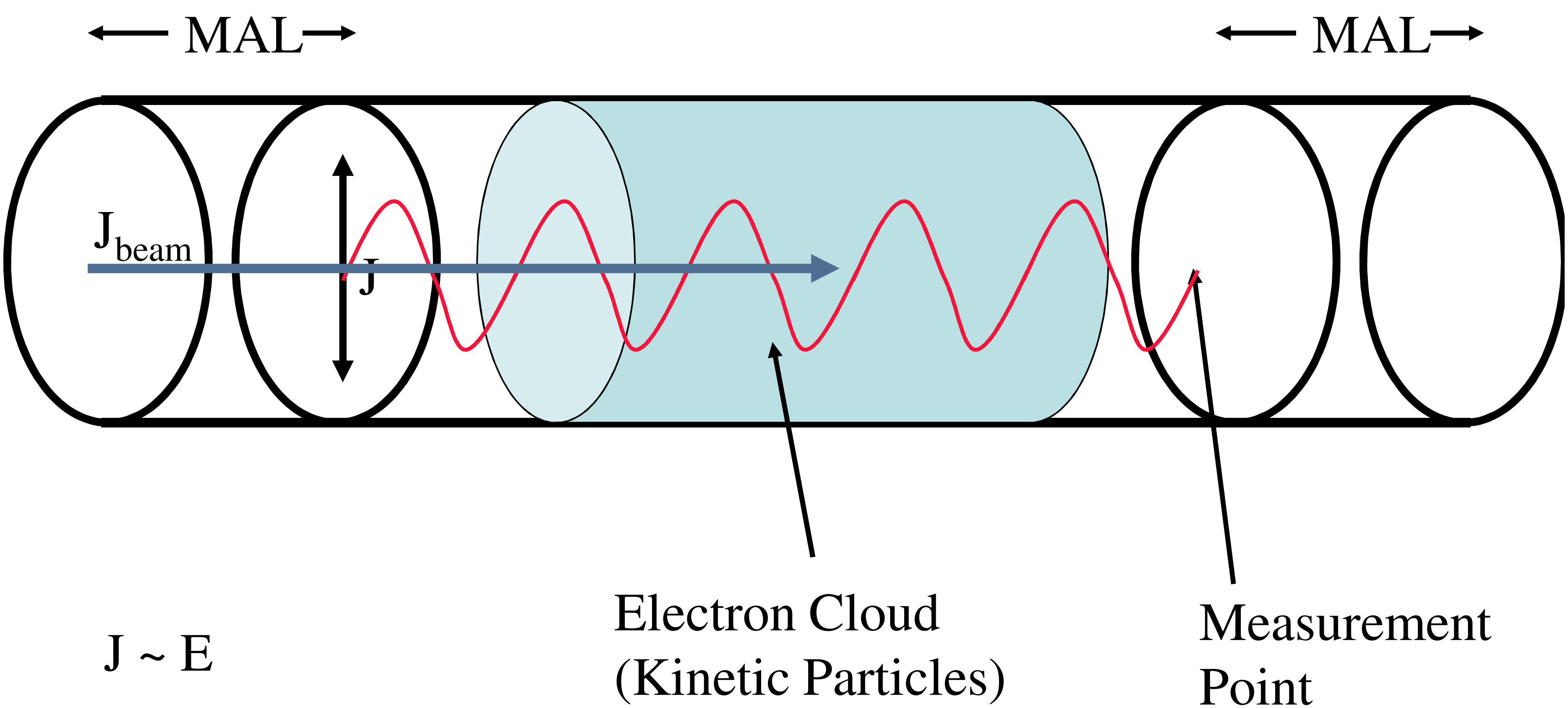


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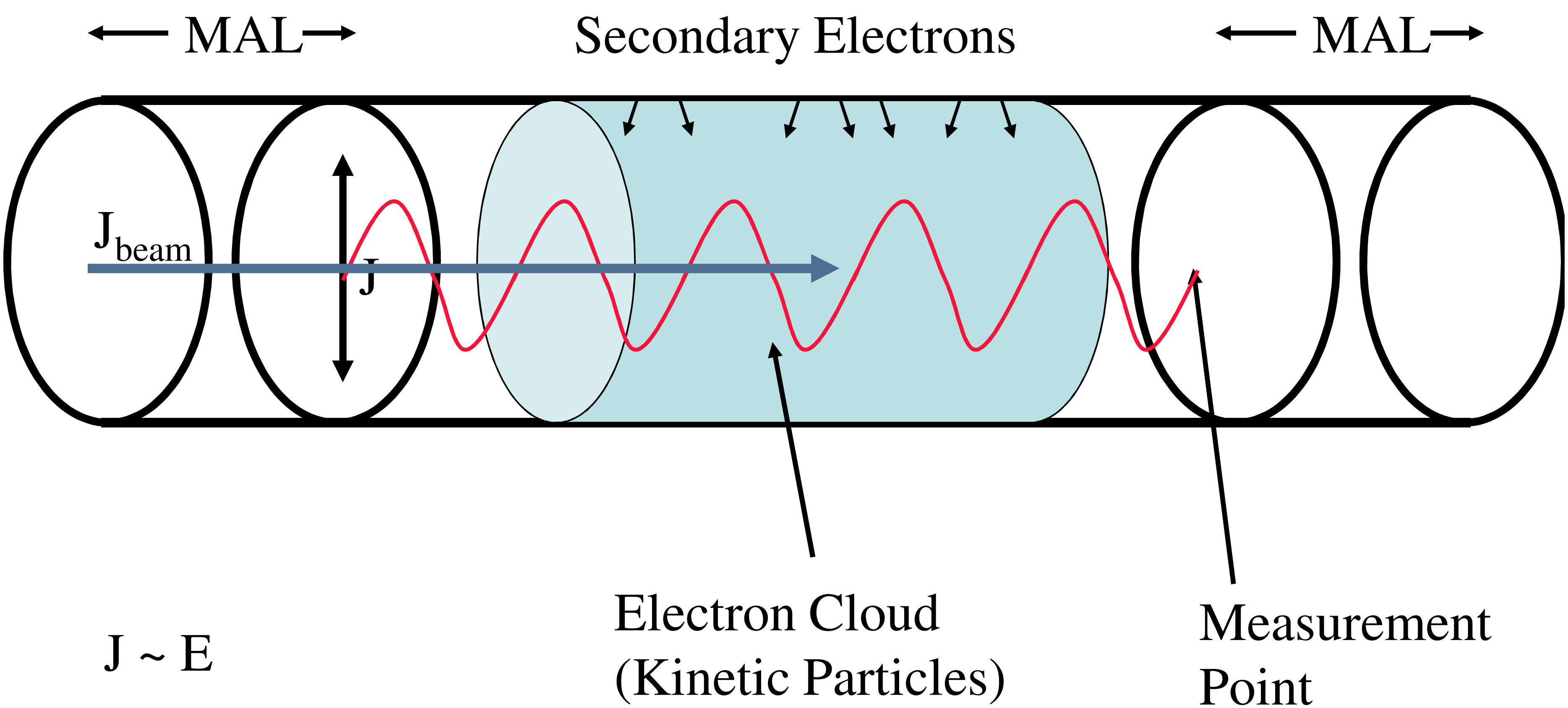


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# VORPAL Simulations

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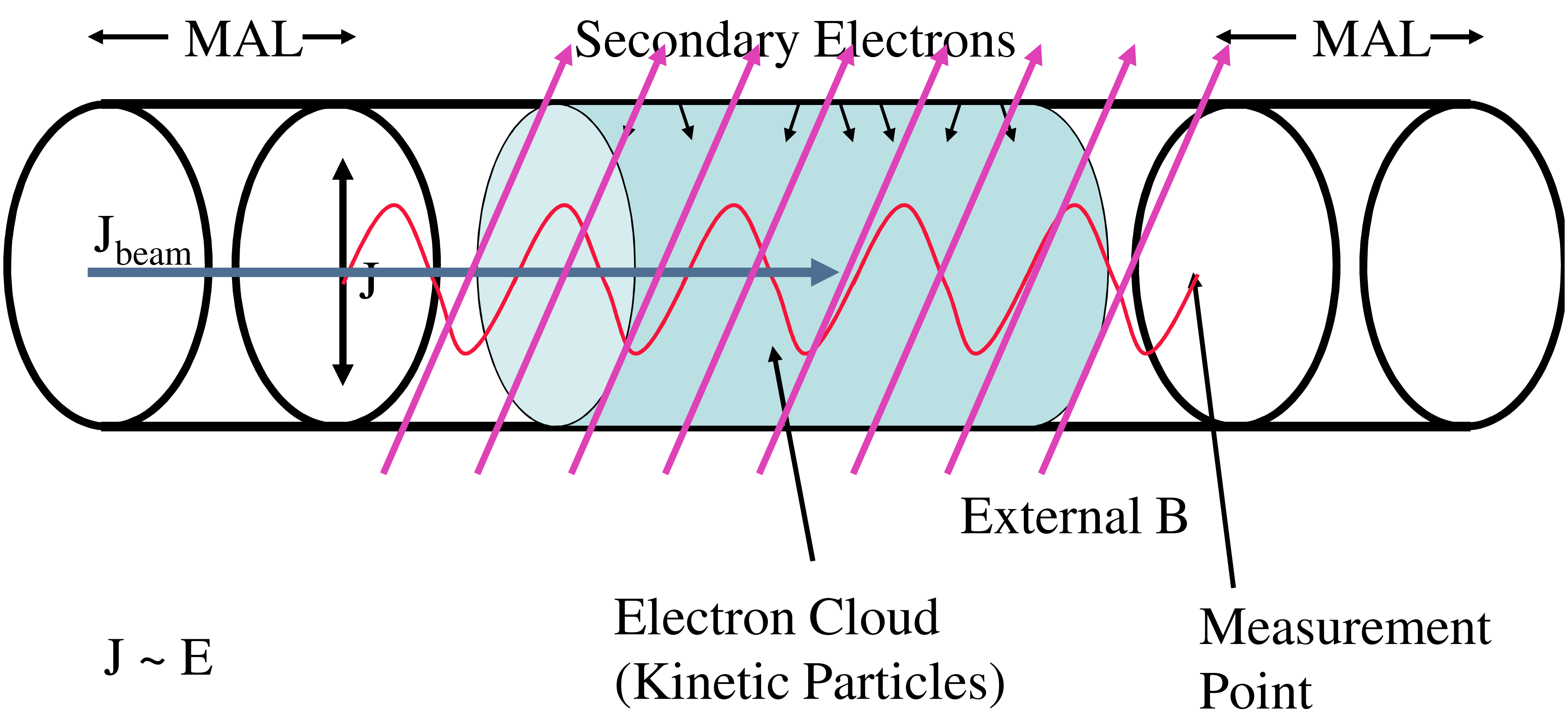
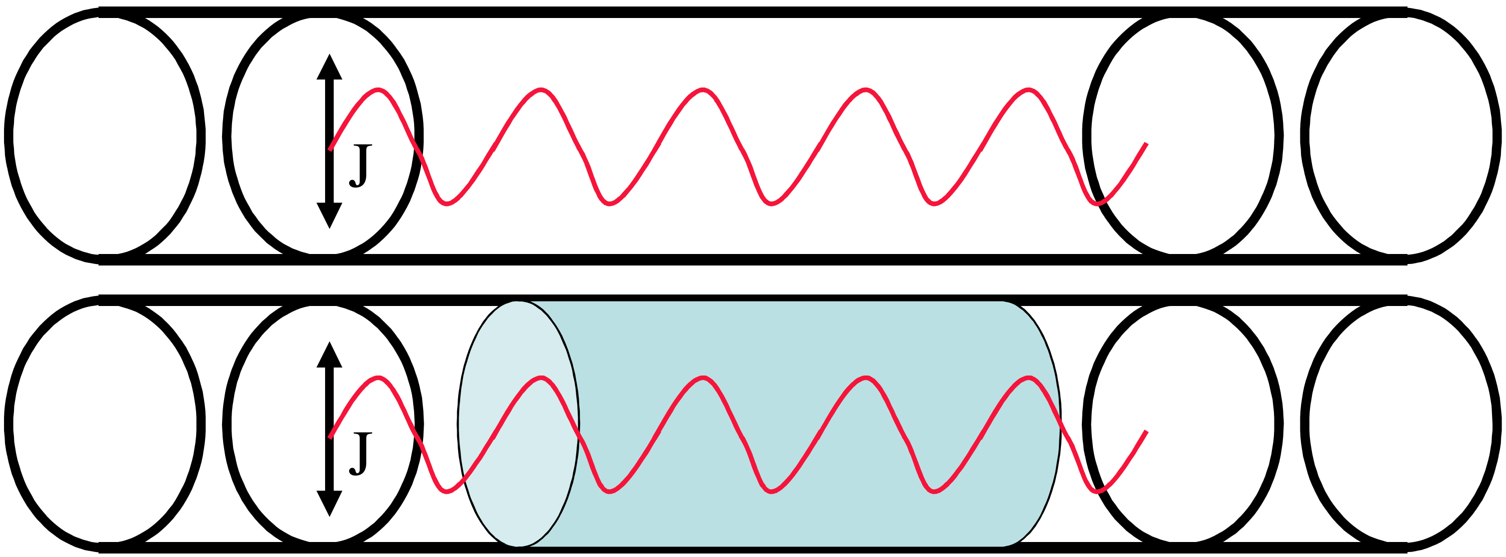


# Direct Simulation of Phase Shifts Due to Electron Clouds

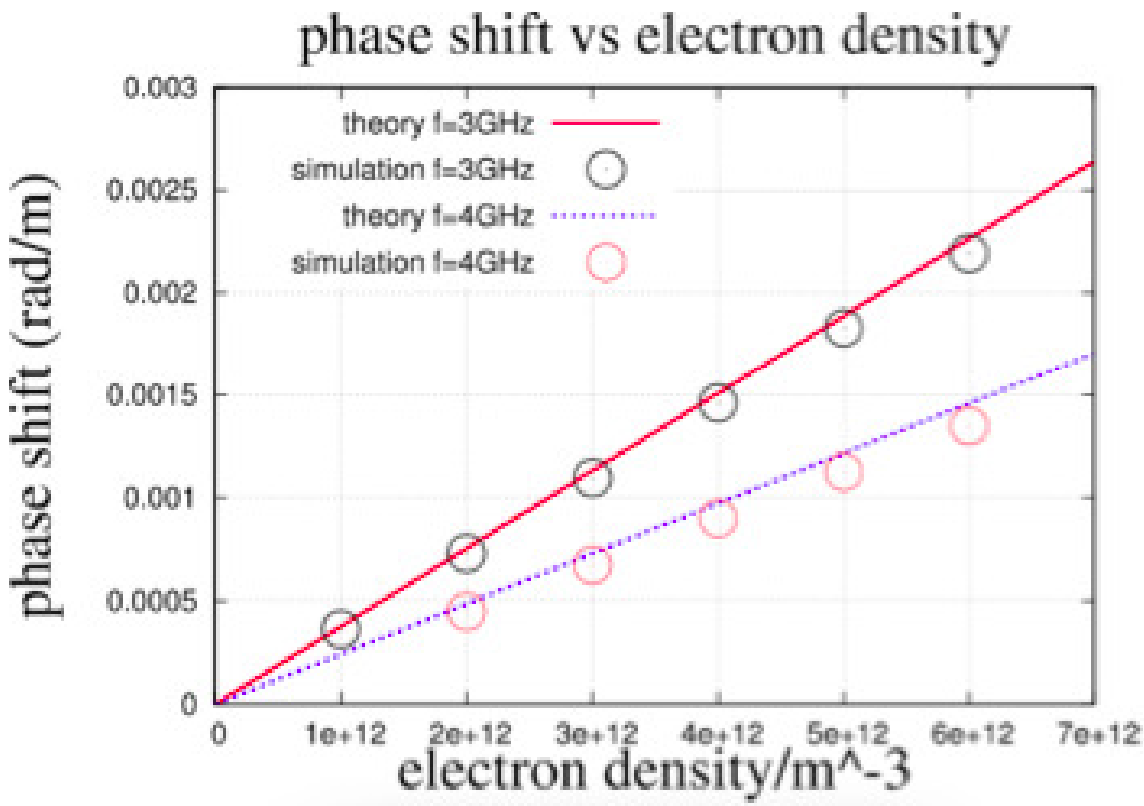



- First perform simulation without any electrons
- Then perform simulations with electron cloud
- Compare time series' and compute phase shifts

# Simulated Phase Shifts Agree With Linear Theory for Uniform Density Clouds

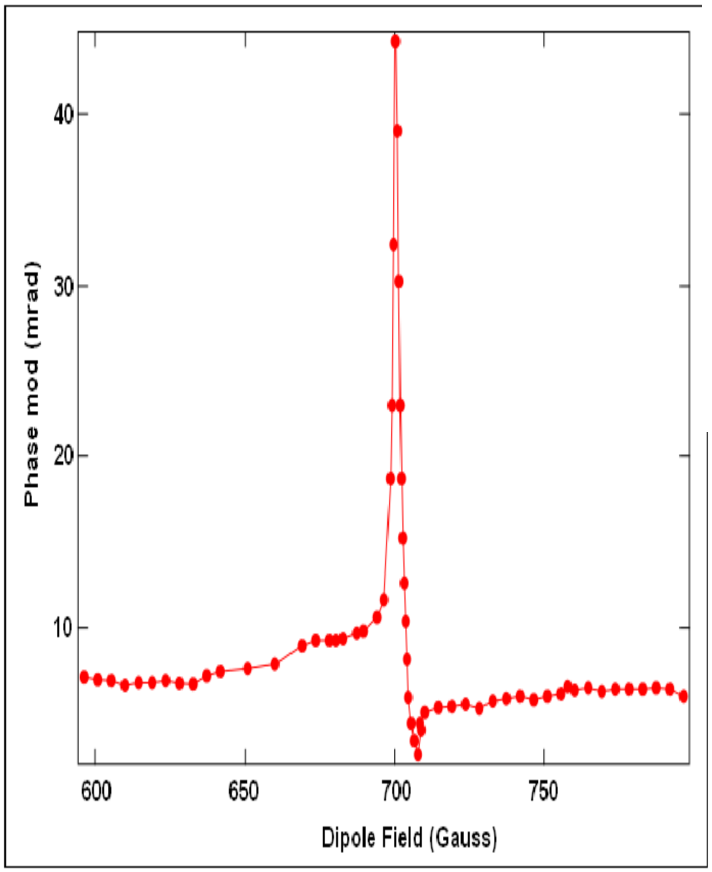
$$\frac{\Delta\Phi}{\Delta L} = \frac{\omega_p^2}{2c(\omega^2 - \omega_c^2)^{1/2}}$$

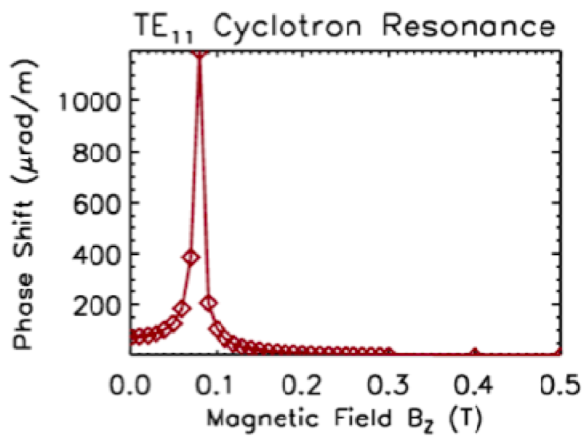
$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}}$$

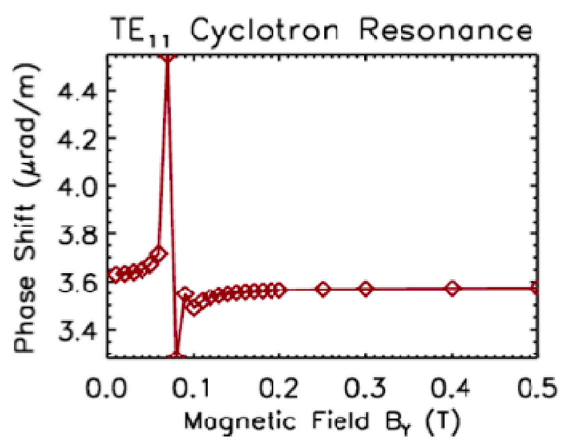



Sonnad et al., PAC07

# We can also simulate the cyclotron resonance using this model




A transverse dipole magnetic field will excite an upper-hybrid resonance if the applied field is normal to the rf electric field

$$\omega_{uh} \approx \omega_{ce} = \frac{qB}{m_e c}$$

Veitzer et al., PAC09

# But electron clouds are not uniform density!

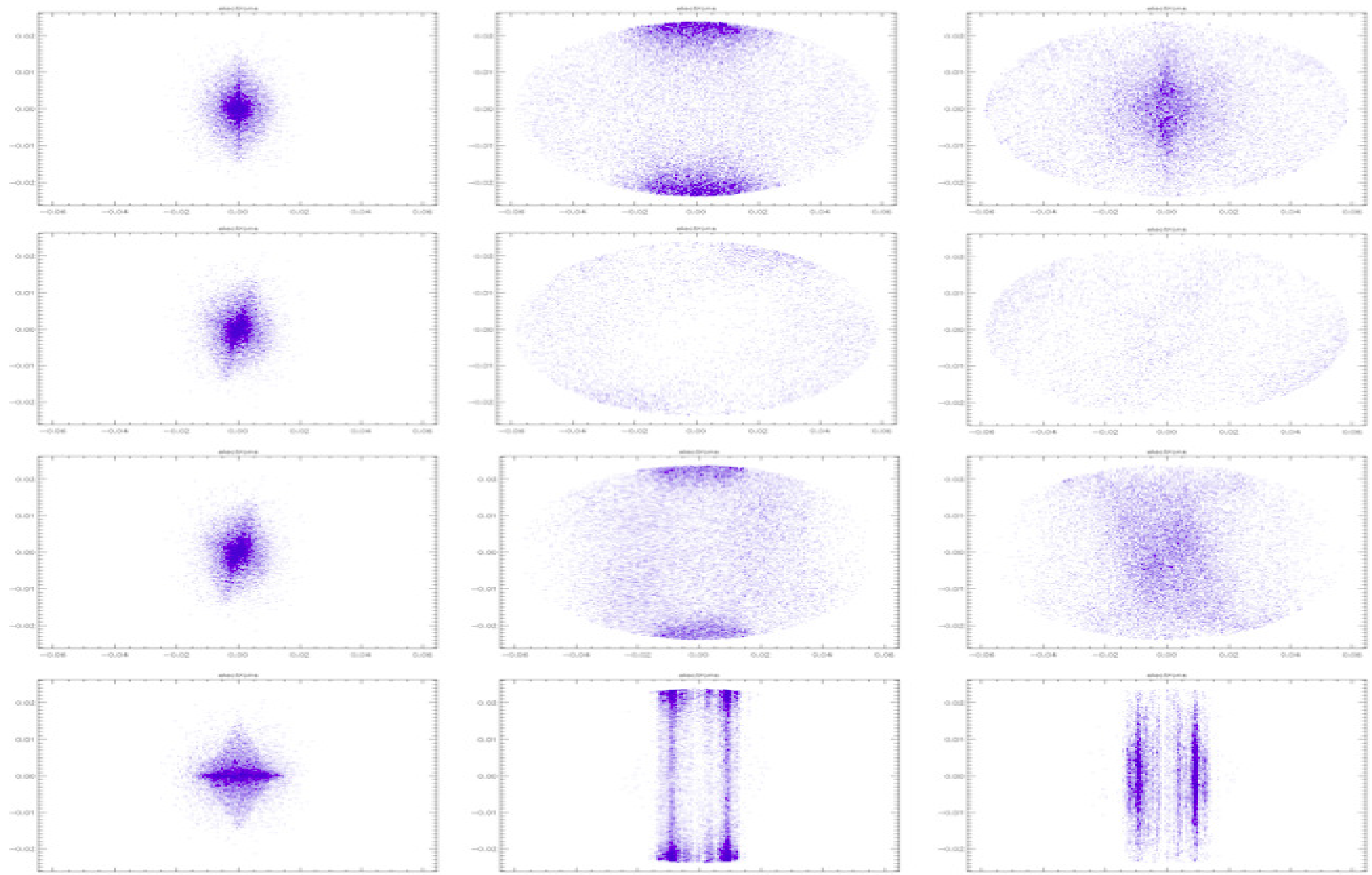
17 ns | 500 ns | 1000 ns

$B = 0$

$B_z = 10$ G

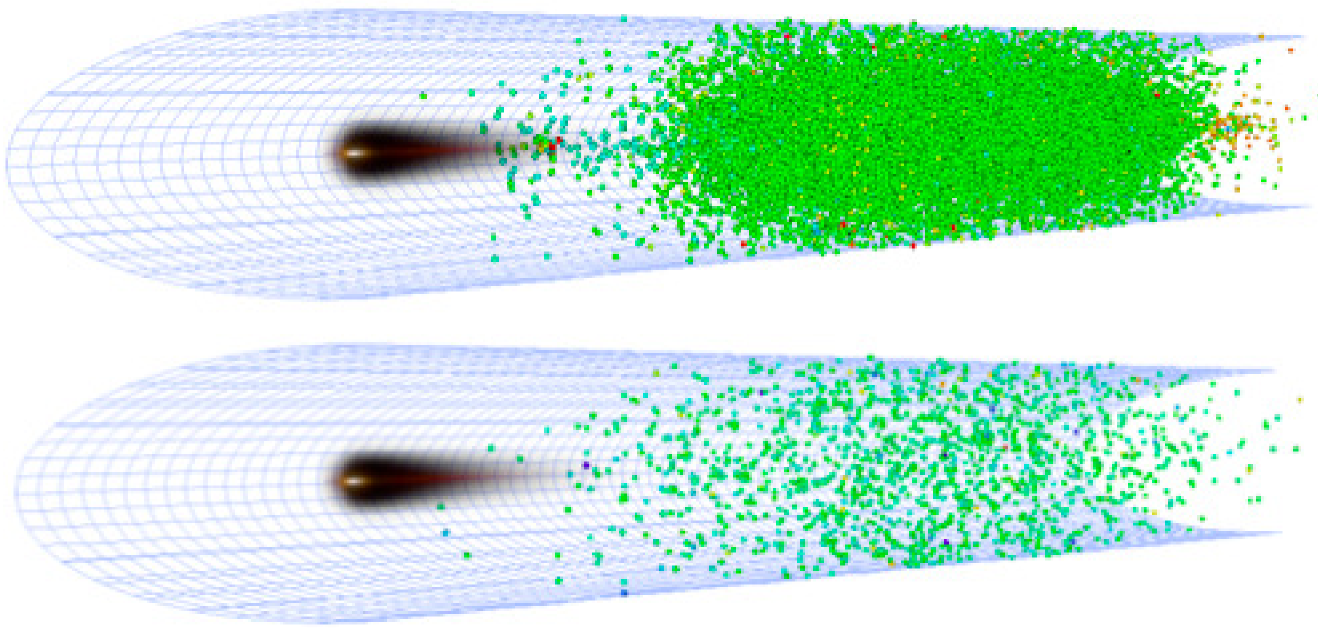
$B_z = 10$ G
$B_y = 10$ G

$B_z = 10$ G
$B_y = 2340$ G



Veitzer et al., J. Phys. Conf. Ser., 2009

# Long Timescale Simulations Can Accurately Model Cloud Buildup



Kinetic electrons are attracted by the beam potential which accelerates them to the pipe walls. Secondary electrons are produced which are attracted by the next bunch.

# Electron cloud distributions depend heavily on magnetic field configurations

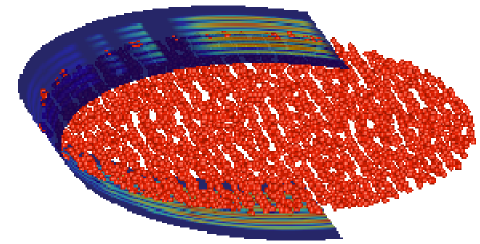
In field free regions, clouds evolve to more uniform densities

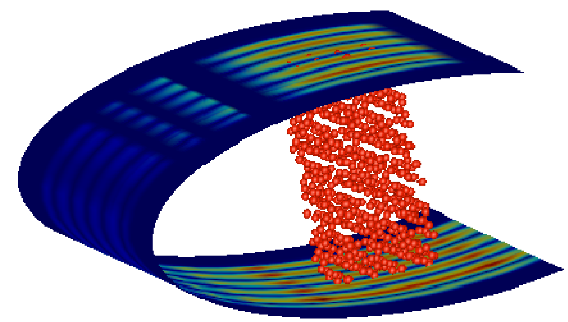
In dipole regions, electrons evolve into vertical striped patterns

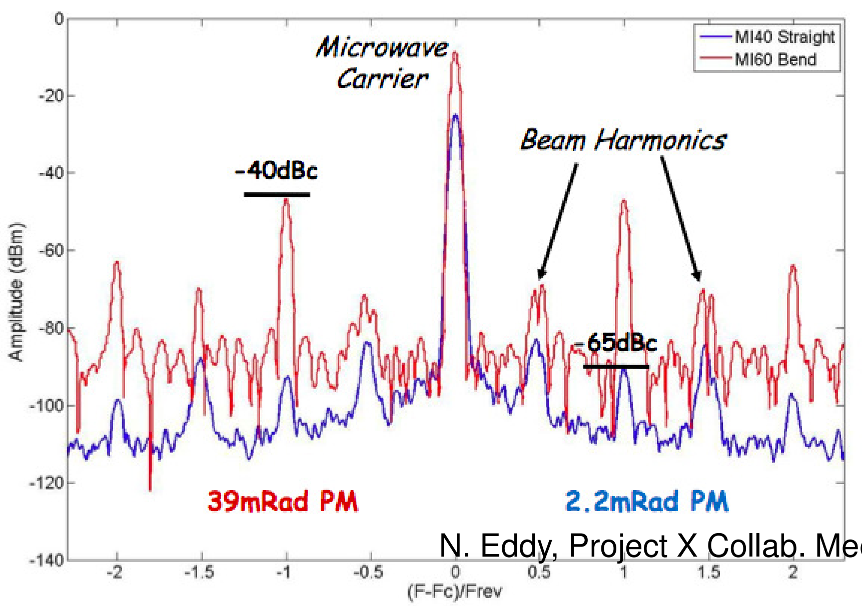
In quadrupole regions, electron density shows an X pattern

Non-uniform cloud density has a significant feedback on theory

Connection between rf side band amplitudes and phase shifts assume uniform density clouds

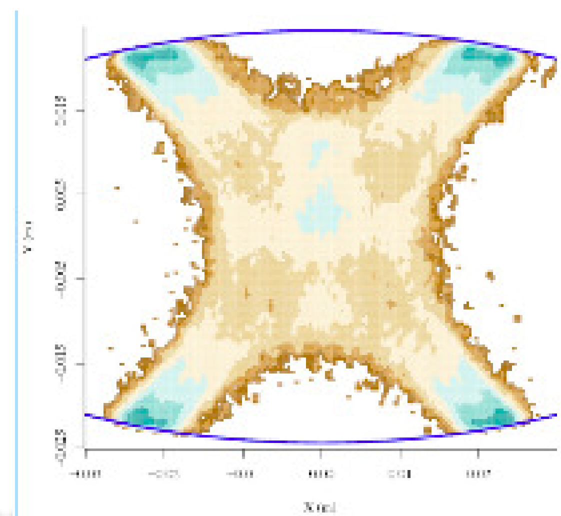




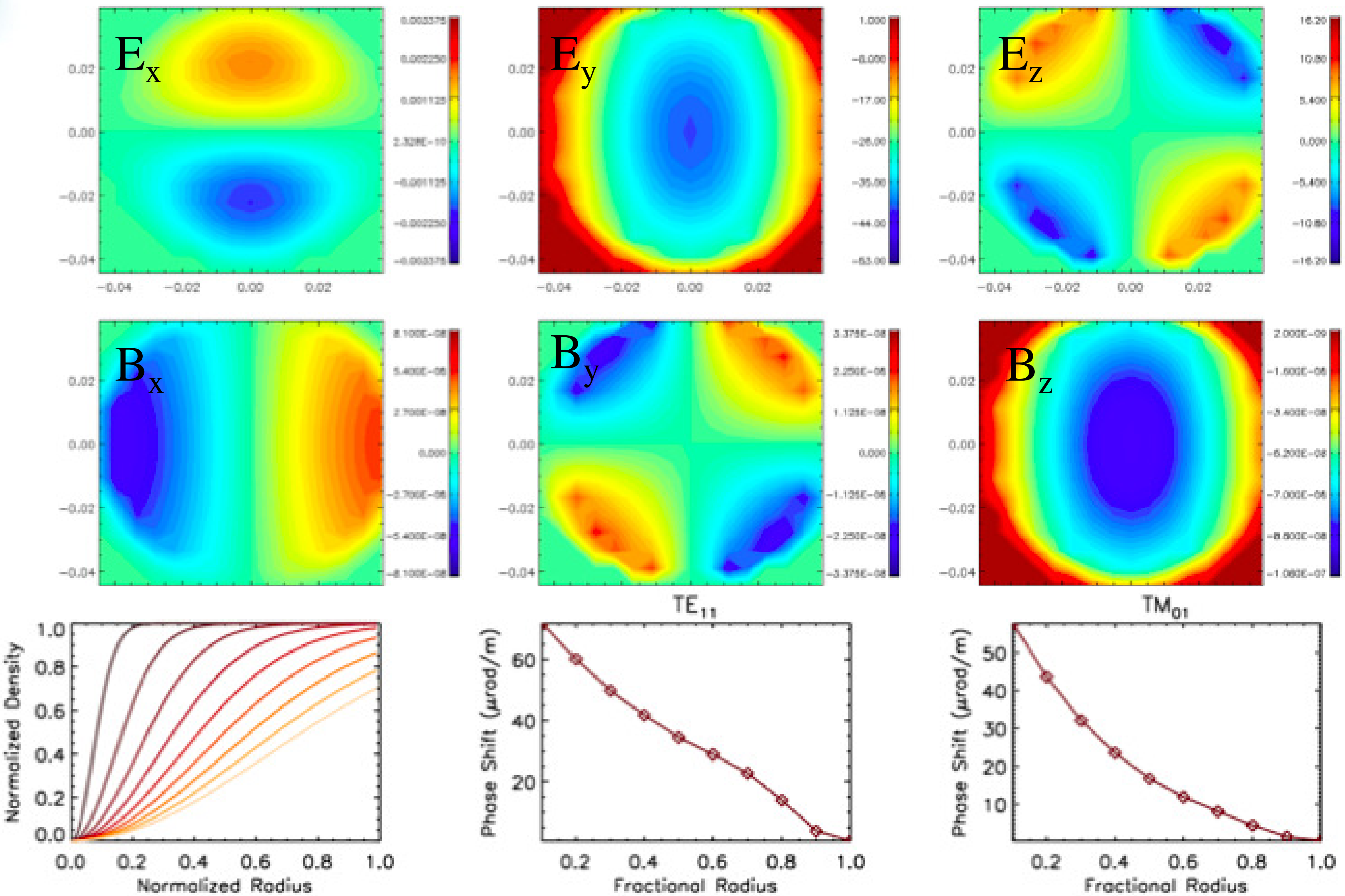



N. Eddy, Project X Collab. Meeting 2009

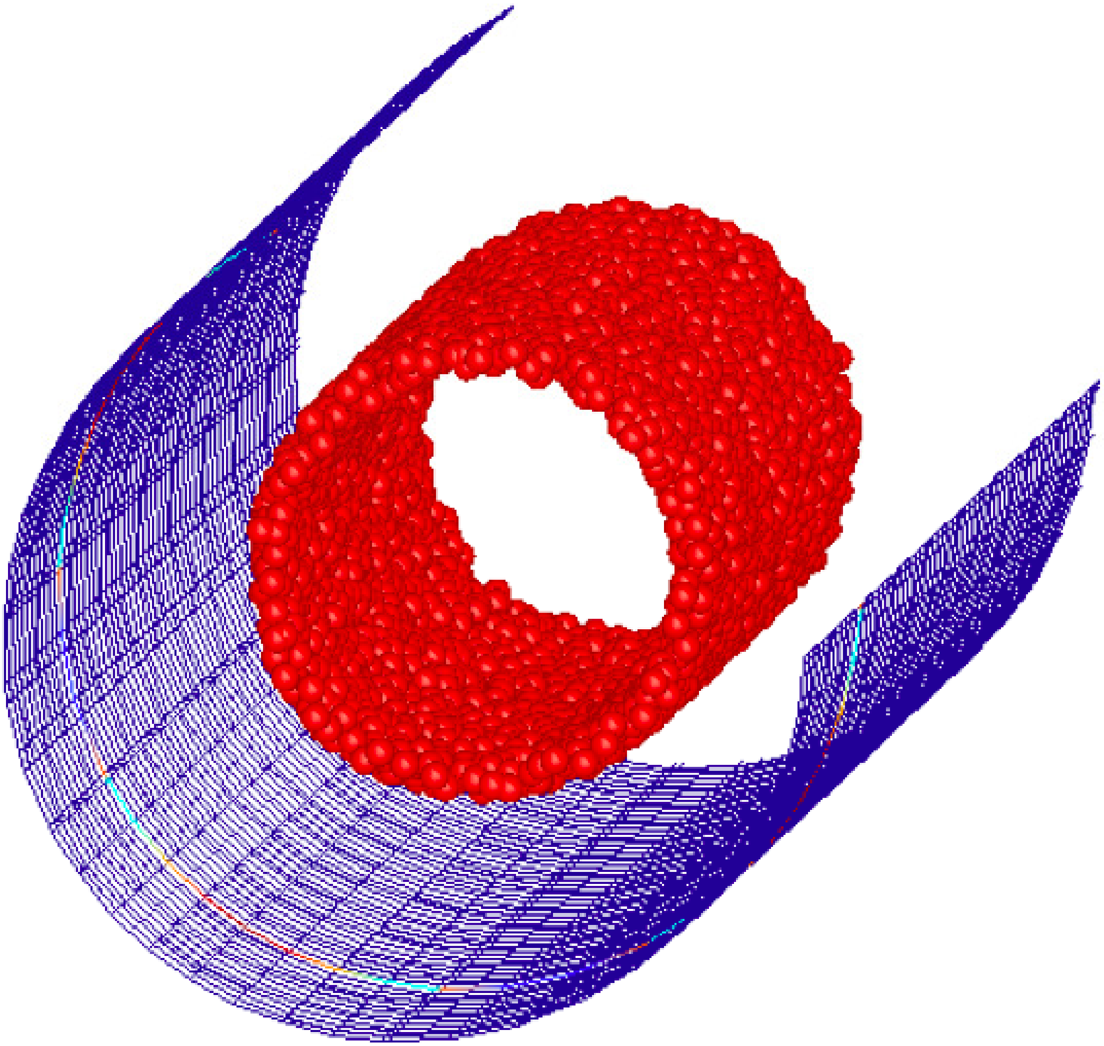
Cf. Lebrun's talk this morning on buildup simulations for the MI



# What is the effect of non-uniformity on rf transmission?

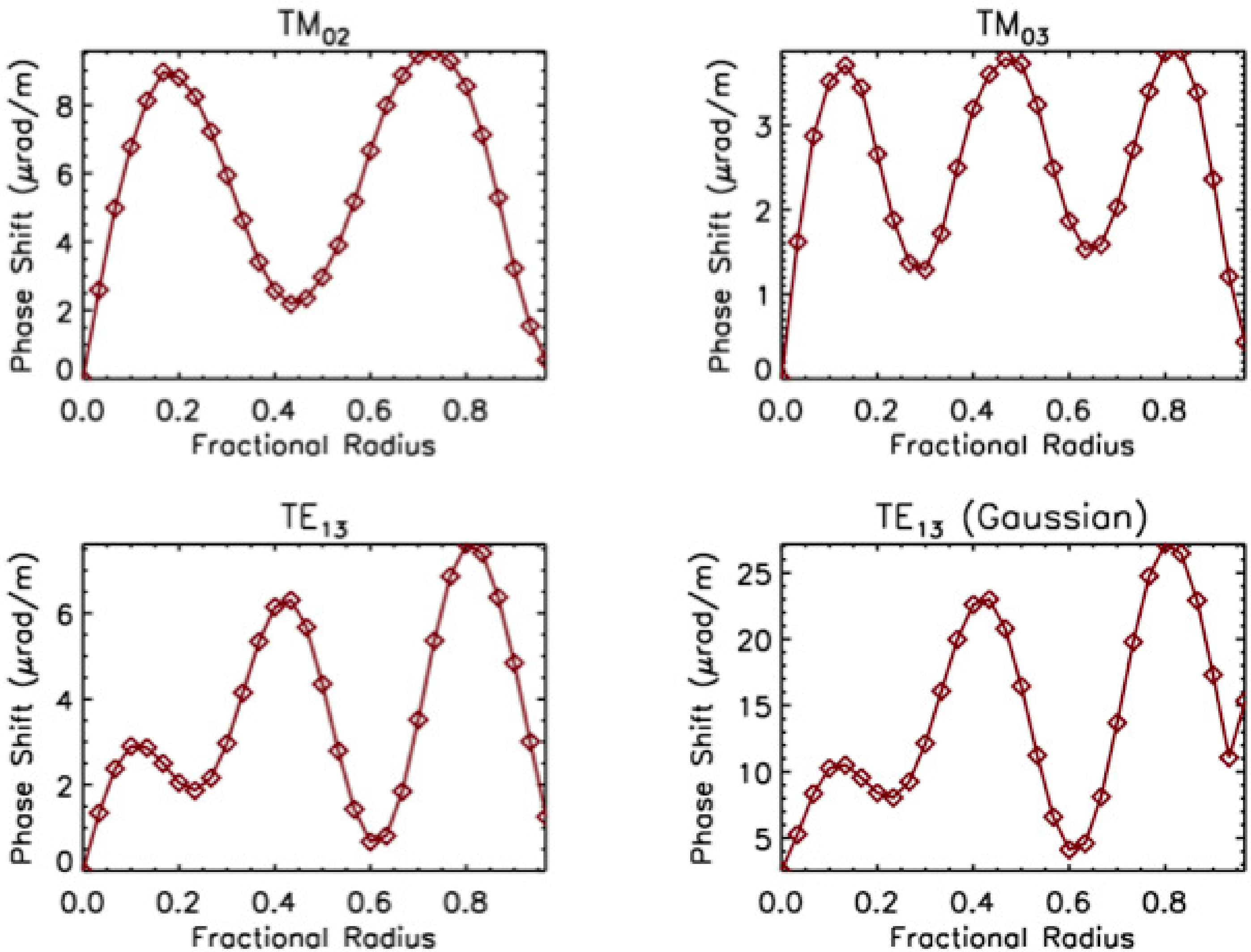


# Can higher order modes measure cloud nonuniformity?



Directly measure the phase shifts through rings of electrons, with TE and TM modes

# Can higher order modes measure cloud non uniformity?

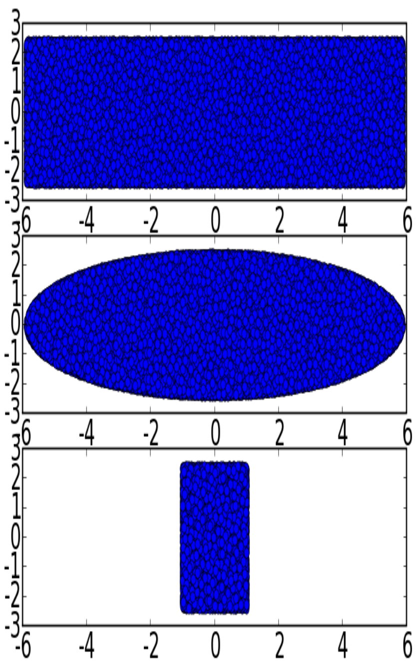


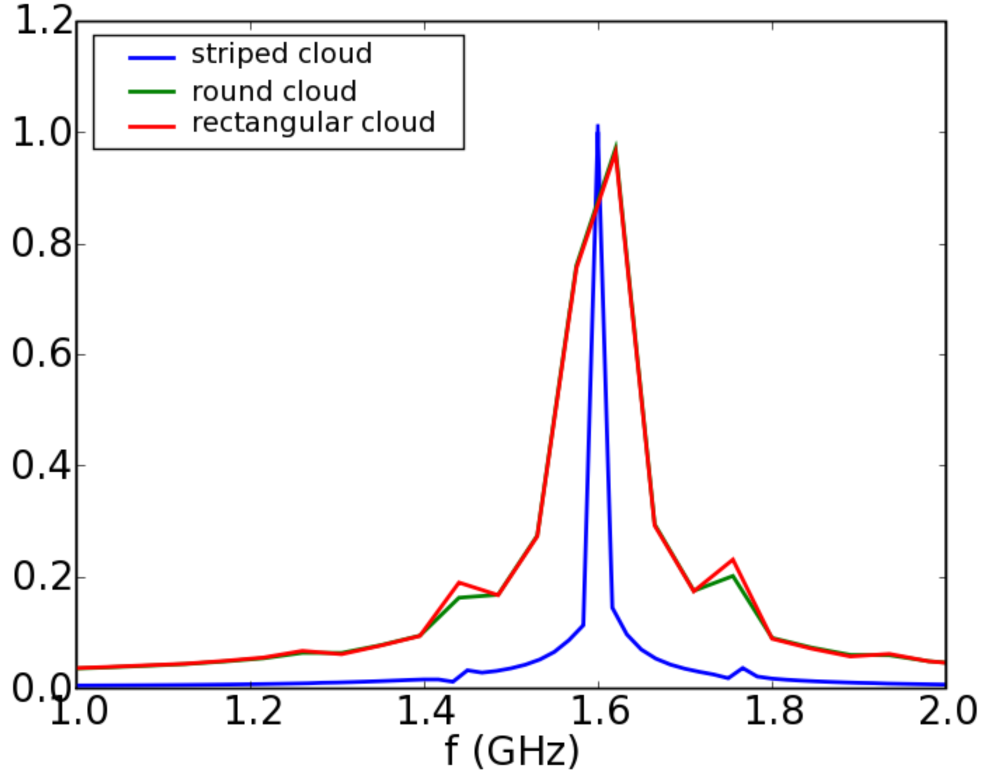
# Correlating Side-Band Amplitudes to Cloud Density is Difficult

- Non-uniform electron distributions mean that TE rf is sampling only part of the cloud
- *-- Maybe not so bad, because TE samples most near the beam location*
- Reflections other structural effects mean that the rf path length through the cloud is not well known.
- Simulation times are large in order to resolve the sideband separation in Fourier space
- For instance, 10 kHz resolution requires at least 200 μs of simulation. At 1 ps time steps that is 2e8 steps.
- Plus, clouds are modulated on a revolution time scale, which is long compared to the time steps
- *Lose the particles, speed up the simulation*

# Reproducing Fourier Signals in Time Domain Simulations

- We can test by simply modulating the cloud density (a clever numerical trick?)






- But numerical noise is still a problem for long time runs (grid heating)

# Electron Clouds Act as a Dielectric With Respect to rf Transmission

- Instead of modeling electrons as kinetic particles (computationally expensive), treat the plasma as a dielectric material (field updates only)

  - Provides significant speedup over kinetic PIC simulations, while maintaining accuracy in phase and frequency shifts due to the plasma

  - Allows for inclusion of magnetic fields in a natural way, through a dielectric tensor

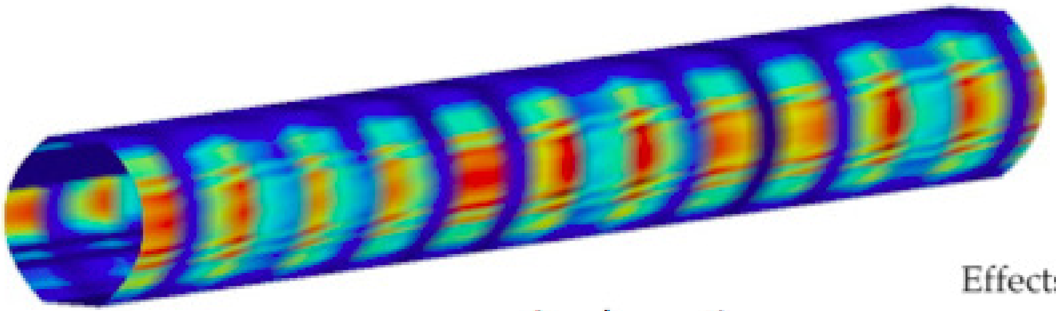
  - Since the plasma dielectric depends on the plasma density (via the plasma frequency) it is straightforward and accurate to simulate non-uniform density clouds

  - Captures the frequency dependence of the plasma response to microwaves

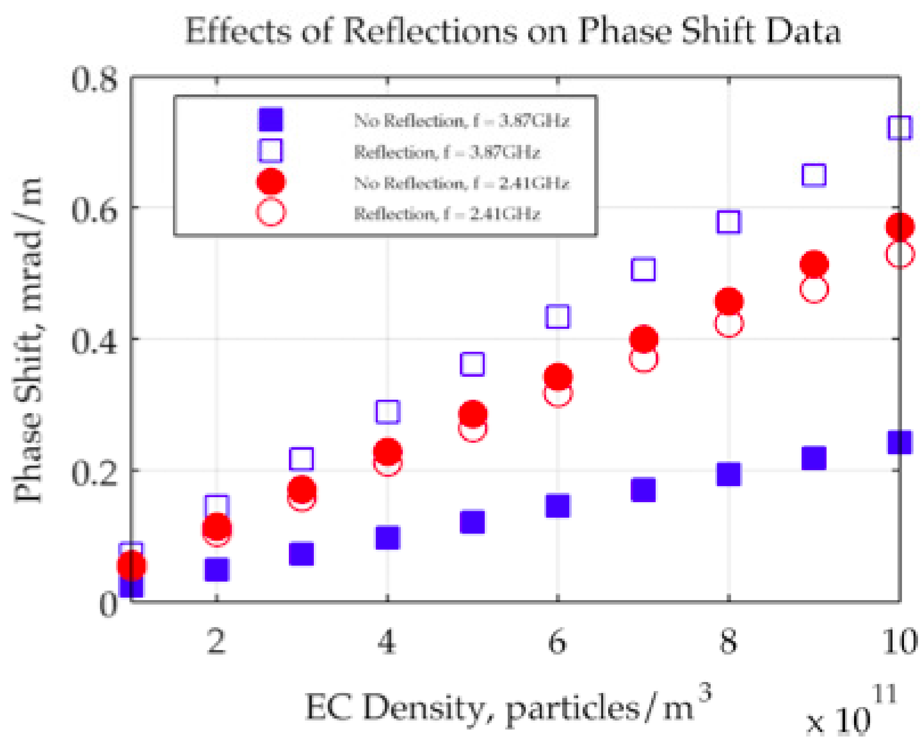
  - The Courant condition remains unchanged, but no particle push!

  - Plasma dielectric model is only valid for cold plasmas, but it is possible to relax the conditions on collisionless plasmas

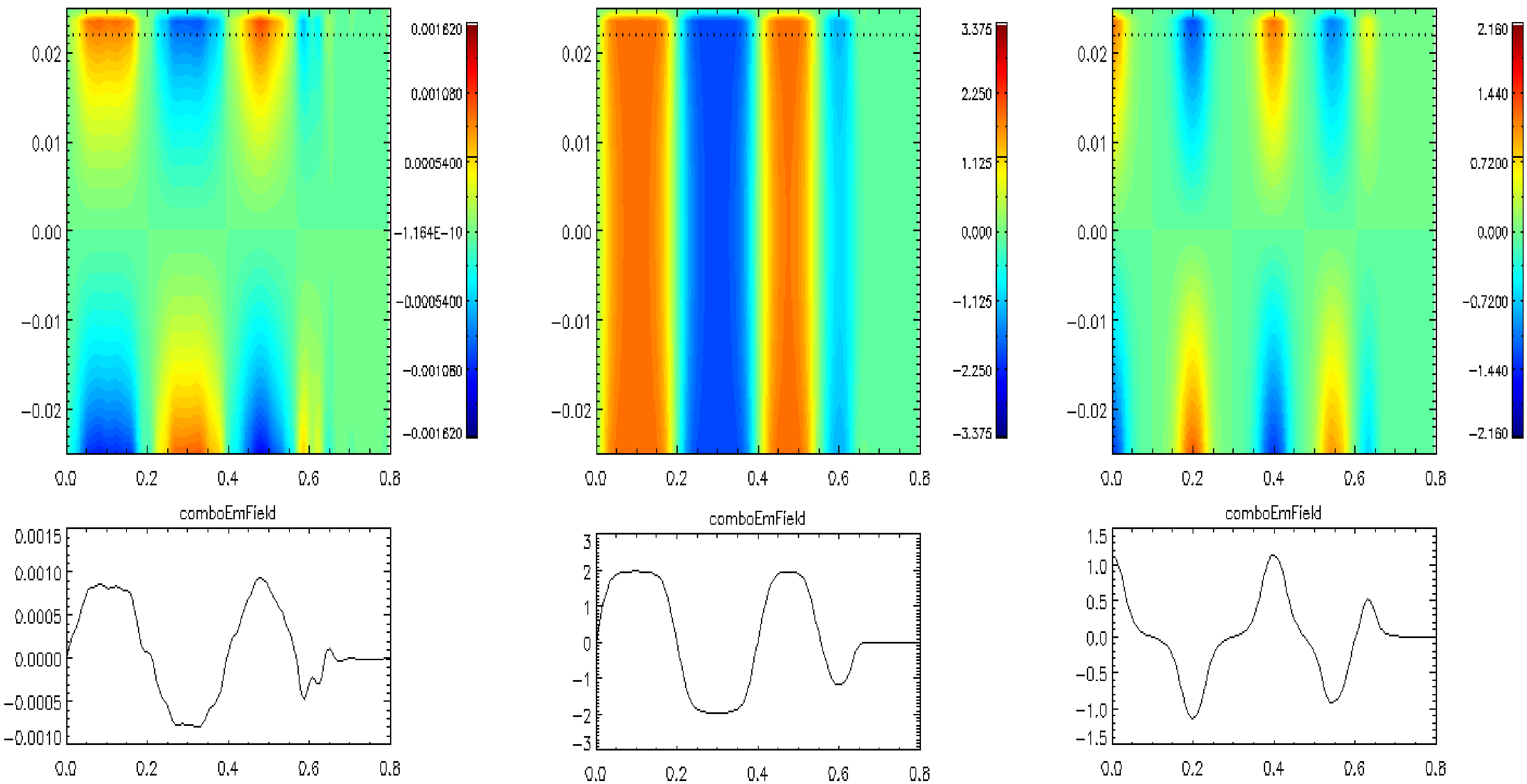
# VORPAL Ecloud Simulations at Cornell



Ken Hammond simulated the effect of reflections on phase shifts using VORPAL

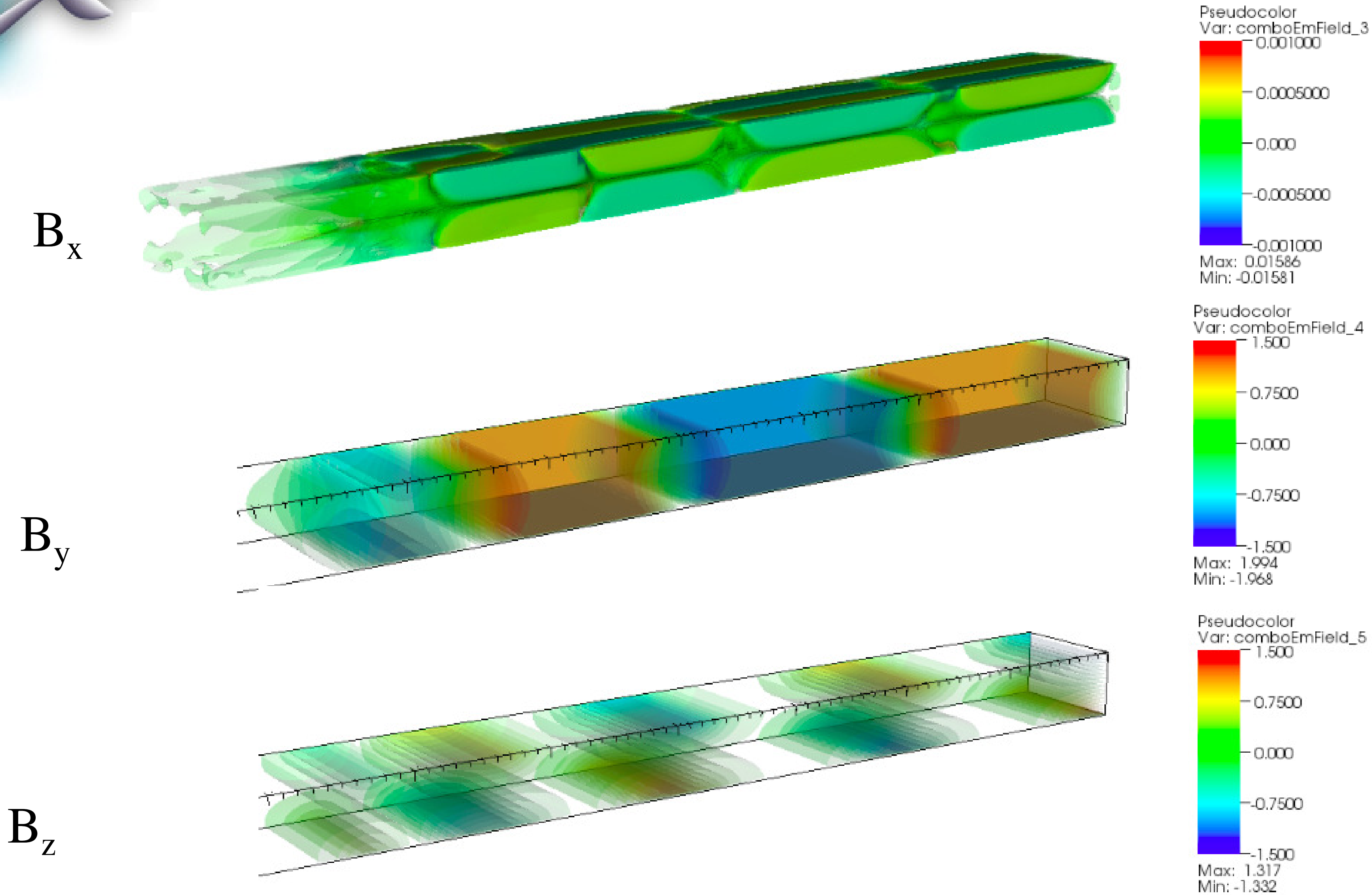


# Wiggler magnetic fields in VORPAL




$B_x$ $B_y$ $B_z$

# Wiggler magnetic fields in VORPAL

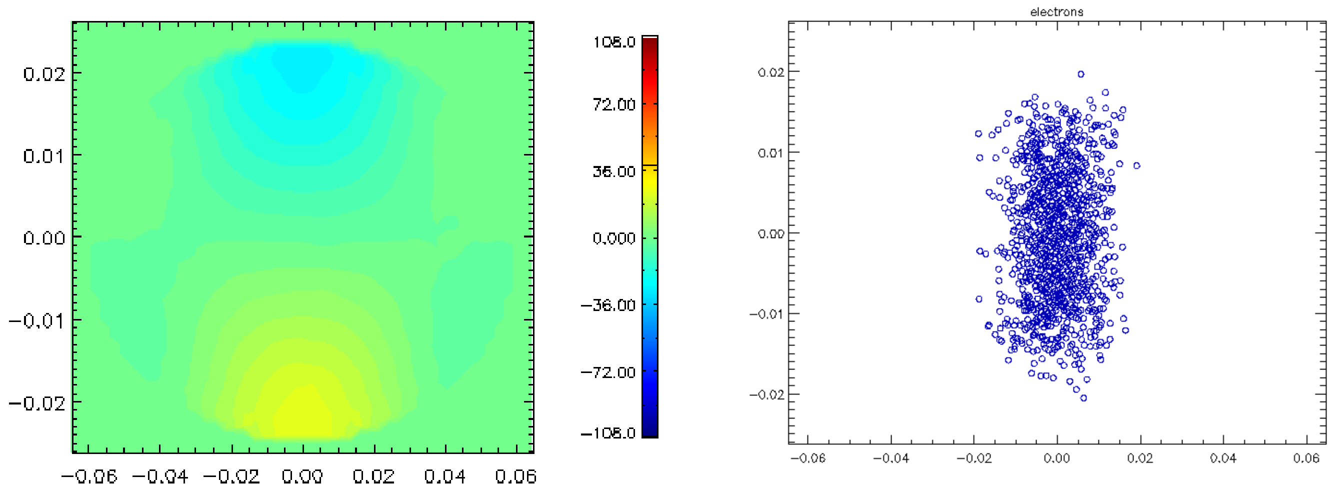


# Current and Future Research

- Add beam, electron clouds, and rf to wiggler simulations
- *Note that electrostatic simulations are more efficient (longer time steps). We plan to add Ron Cohen's pusher to VORPAL so that we can accurately model electron orbits without resolving the cyclotron motion. However, we will also continue with electrodynamic simulations in order to model rf transmission. Plasma dielectric model here too?*
- Comparison between 2-D electrostatic and 3-D electromagnetic simulations
- Modeling electron clouds as a dielectric plasma instead of kinetic particles
- Detailed modeling of RFA response to traveling wave microwave signals
- Measure realistic beam pipe responses to traveling wave microwave diagnostics

# Current and Future Research

- Comparison between 2-D electrostatic and 3-D electromagnetic simulations




- Modeling electron clouds as a dielectric plasma instead of kinetic particles
- Detailed modeling of RFA response to traveling wave microwave signals
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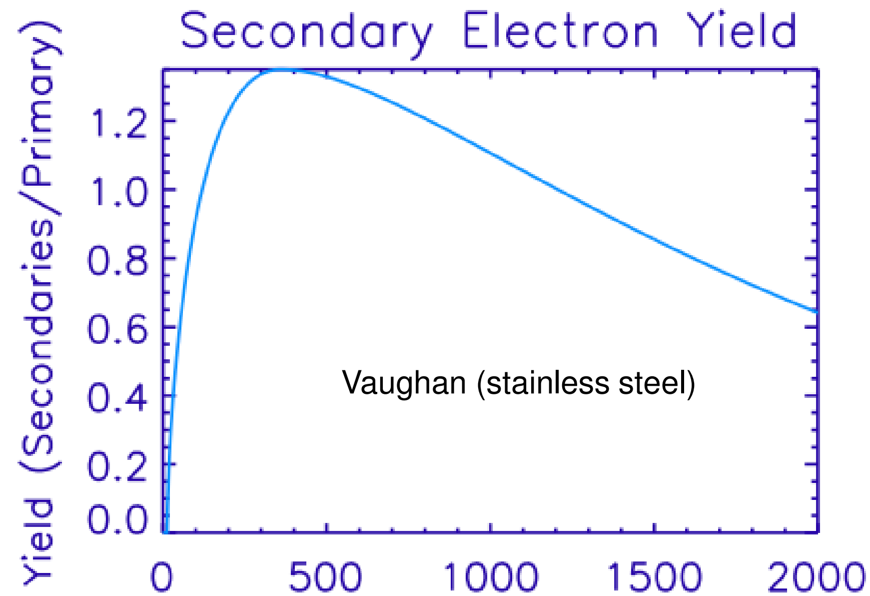
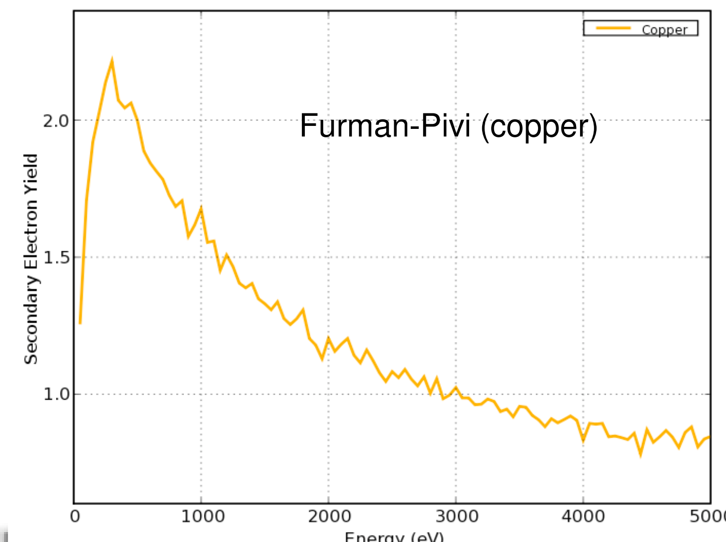
# Additional Topics

# Comparison of Secondary Electron Models Used in Simulations

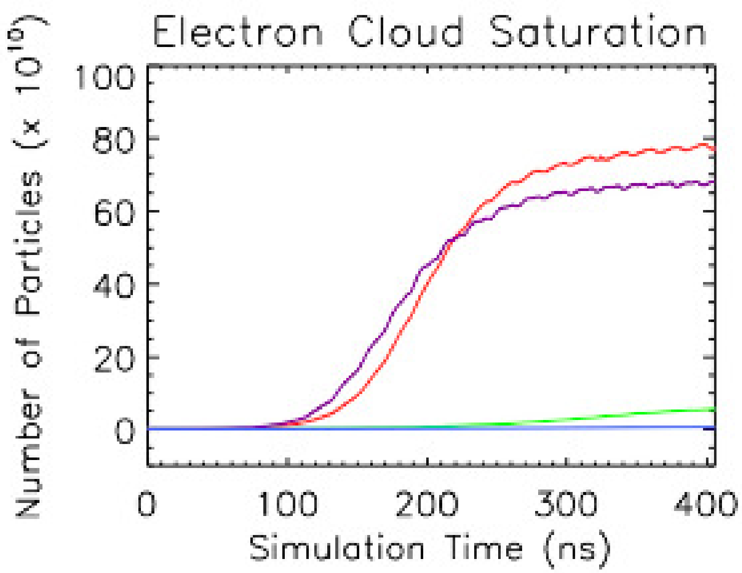
- Cloud buildup depends intimately on the secondary electron model
- We have considered two models; The Vaughan model and the Furman-Pivi model.
- Both the shape of the SEY curve and the value of the maximum of the SEY contribute to the electron cloud growth rate
- In VORPAL, we can model the SEY as either Vaughan or Furman-Pivi, and rescale the maximum of the SEY



# SEY Model Comparisons

- The cloud saturates quickly when the maximum SEY is large
- (red) FP model with $SEY_{max} = 2.0$
- (purple) V model with with $SEY_{max} = 3.6$
- Slower growth is seen when the maximum SEY is lower
- (blue) V model with $SEY_{max} = 1.8$
- (green) V model with $SEY_{max} = 1.0$




P.H. Stoltz, SciDAC 2010

- Decay time is about 40 ns in the dipole case, not short enough to kill the electron cloud in between Main Injector bunch trains

300 ns ~ 1/4 MI revolution period