3-Dimensional Modeling of Electron Clouds In Non-Uniform Magnetic Fields

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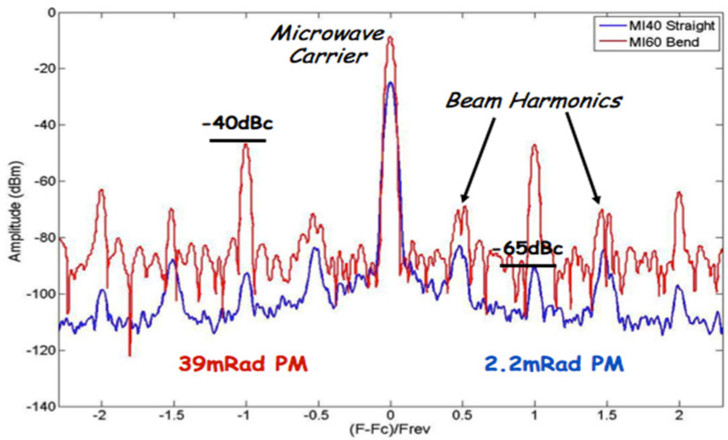
Electron Clouds Can Limit Accelerator Performance

- Low density electron plasmas can form in circular accelerators via synchroton radiation or stray beam particles striking beam pipe walls
- Primary electrons are accelerated by subsequent beam bunches which then create secondary electrons
- Although the plasma is low density (~10^{11} – 10^{13} e^-/m3), they can cause beam instabilities that limit accelerator performance
- This is especially a concern for new high-performance accelerators such as the ILC and Project X
- Electron clouds are modulated on a revolution timescale by gaps in the bunch train, where the plasma dissipates to the walls
- Travelling wave rf diagnostics can measure time-averaged cloud densities by detecting this modulation



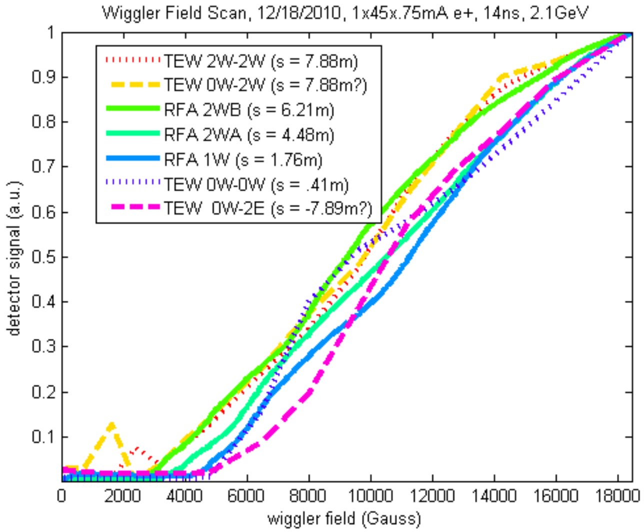
N. Eddy, Project X Collab. Meeting 2009

Numerical Models Provide Methods For Deriving Cloud Densities

- Spectral signals depend not just on cloud density, but also amplitude changes (generally thought to be small), path length through the cloud (often unknown), spatial distribution of electrons (time-dependent), and magnetic field configuration
- Phase shifts (linear approximation, no B field):

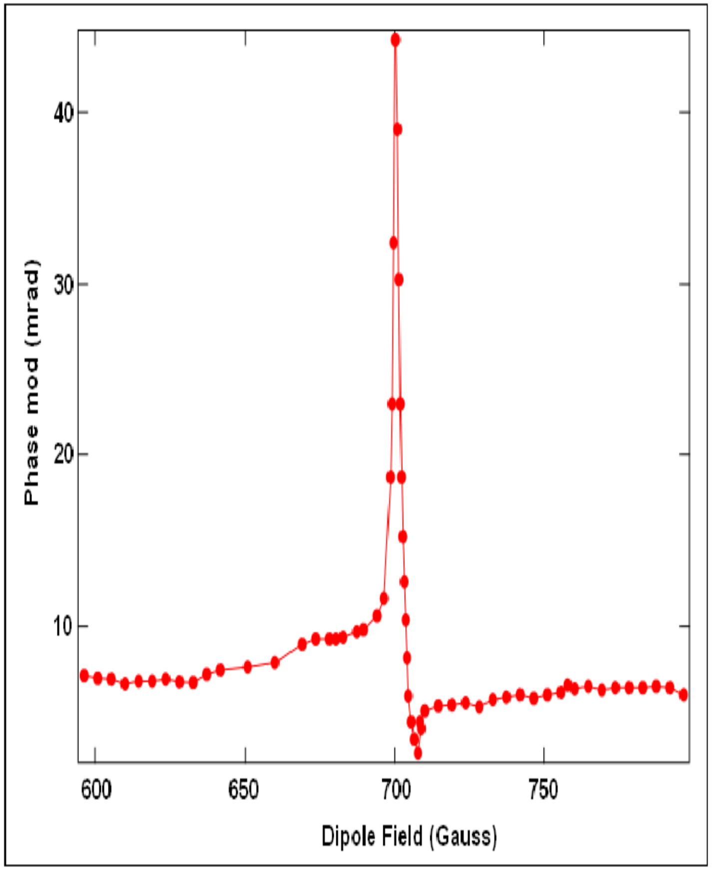
$$\Delta\phi / \ell = \frac{\pi}{c} \frac{f_p^2}{\sqrt{f^2 - f_{co}^2}}$$

$$f_p \approx 8990\sqrt{n_e \cdot 10^{-6}} \quad MKS$$



- Accurate simulations are able to model both cloud build up, and microwave transmission diagnostics
- Reproducing spectra requires very long simulations in order to resolve modulation frequencies (hundreds of kHz to tens of MHz)
- Determining phase shift effects for different model parameterizations (cloud density, magnetic field configuration, etc) is more manageable

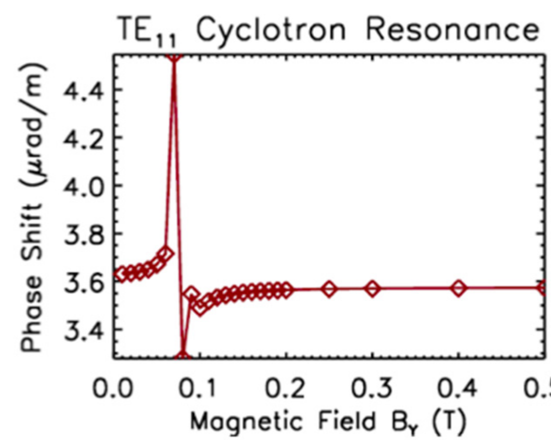
Magnetic Fields Can Have A Big Effect On Phase Shifts



- Cyclotron resonances have been shown to have a significant effect on plasma-induced phase shifts for a given plasma density in both experiment and simulations
- Depends on both the strength and orientation of the magnetic field
- Upper hybrid resonance occurs when the magnetic field is normal to the rf polarization (X-Wave)
- No resonance when magnetic field is parallel to the rf polarization (O-Wave)

$$\omega_{uh}^2 = \omega_p^2 + \Omega_e^2 \approx \frac{eB}{m_e c}$$

$$\omega_p \approx 10 - 30\,MHz$$

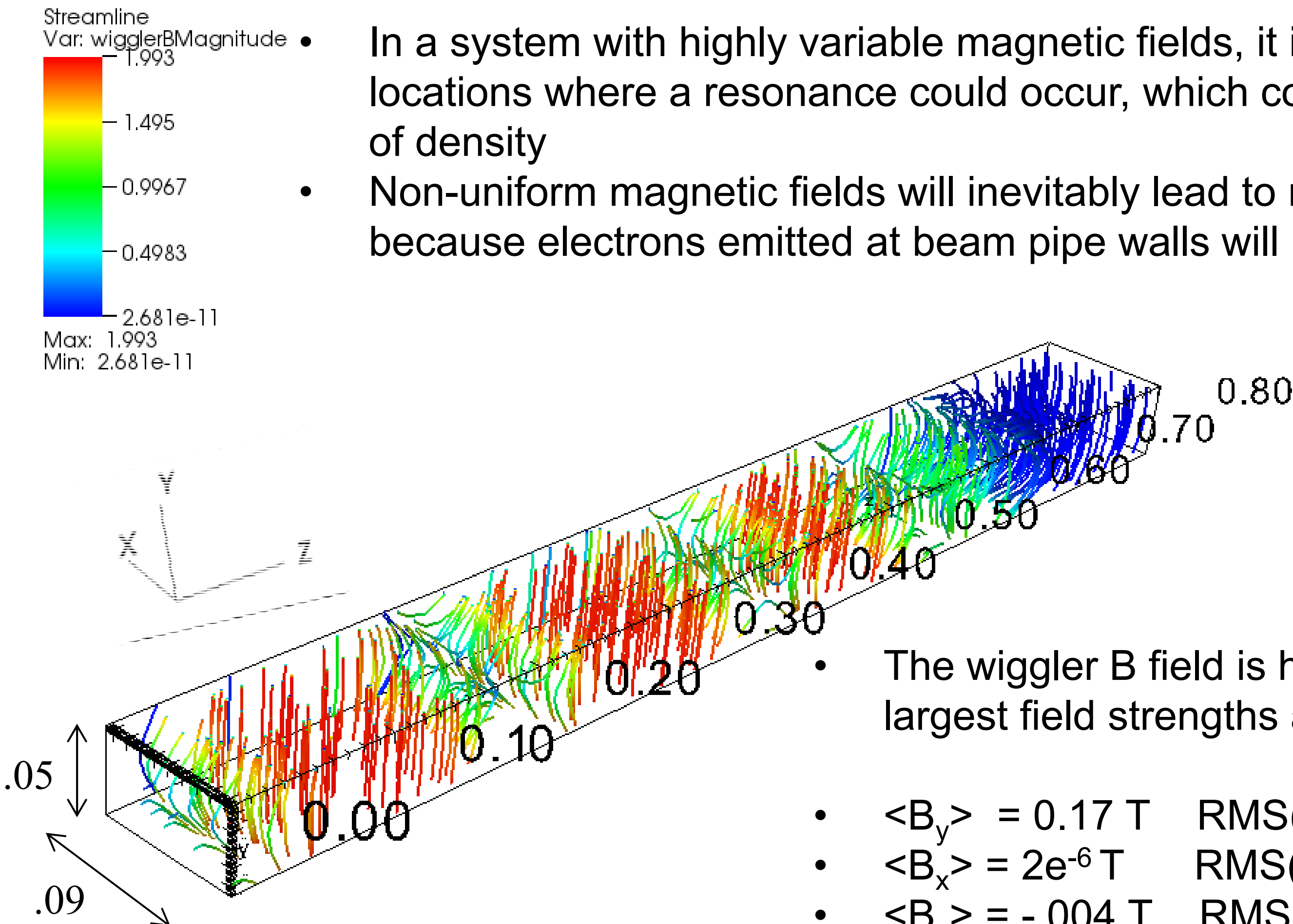


Celata , Furman *et al.* EPAC08
Veitzer *et al.* PAC09
DeSantis, Byrd, *et al.* PAC11
and others

Veitzer et al PAC09,

Spatially Non-Uniform B Fields May Have A Big Effect On Phase Shifts

- In a system with highly variable magnetic fields, it is possible that there are locations where a resonance could occur, which could cause misinterpretation of density
- Non-uniform magnetic fields will inevitably lead to non-uniform cloud densities because electrons emitted at beam pipe walls will be pinned to the field lines

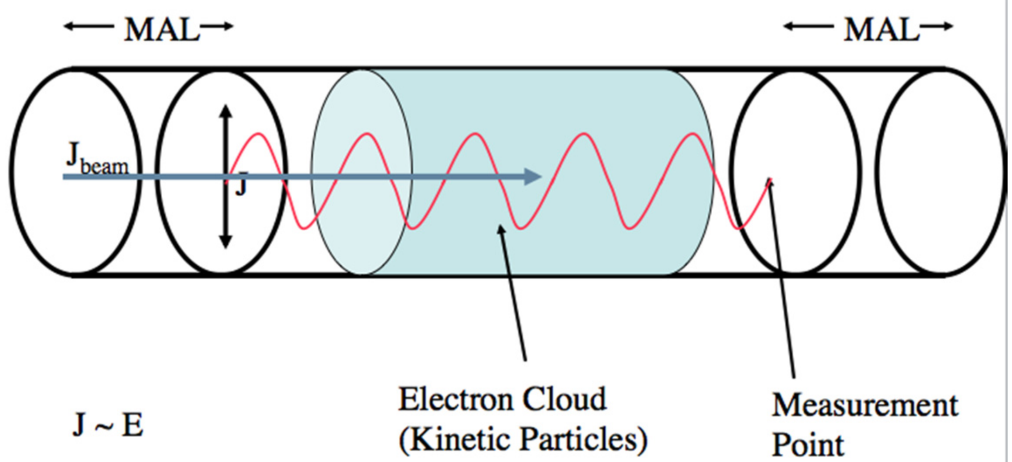


- The wiggler B field is highly non-uniform, and the largest field strengths are in the y-direction (~ 2T)

- $\langle B_y \rangle$ = 0.17 T RMS(B_y) = 0.976 T
- $\langle B_x \rangle$ = 2e^{-6} T RMS(B_x) = .003 T
- $\langle B_z \rangle$ = -.004 T RMS(B_z) = 0.5 T

New Algorithms Improve Simulation Accuracy And Speed

- Previous Vorpal simulations of traveling wave rf diagnostics contained a current source to launch rf into the plasma, and either PMLs or MALs to absorb rf at the ends of the wave guide
    - This produced a fair amount of broadband noise due to the finite extent of the current source

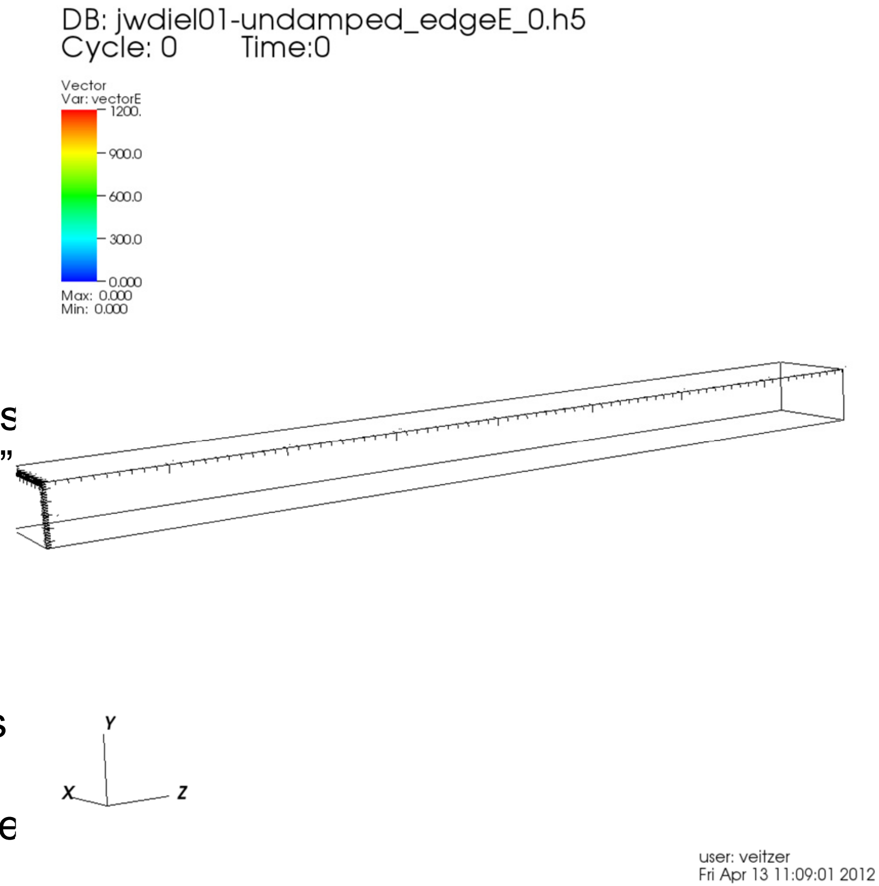


- Self-consistent kinetic particles provided estimates of phase shifts
- Cloud build up simulations have also been extensively performed using POSINST, Warp, Vorpal, and other simulation codes
    - It is important to use kinetic particles in build up simulations in order to capture wall effects (SEY) and cloud evolution due to beam passages
- However, for modeling rf diagnostics it is the dielectric properties of the plasma that are important, and the cloud density does not significantly evolve over simulation time scales (hundreds of rf periods)
    - *Caveat*: Clearly density evolution is important when considering non-uniform clouds

New Algorithms Improve Simulation Accuracy And Speed

- New port boundary conditions absorb a single dominant frequency, and can simultaneously launch a wave into the domain

- We use a new plasma dielectric model for the electron plasma instead of kinetic PIC particles
    - Plasma dielectric model accurately reproduces plasma-induced phase shifts
    - This eliminates so-called “particle noise” that arises from interpolation of particle charge and currents to the computational grid
    - Plasma dielectric model is faster than traditional PIC, because particle pushes are expensive
    - This reduces disk requirements because no particle dump files are produced
    - Does not address evolution of cloud density due to non-uniform magnetic fields



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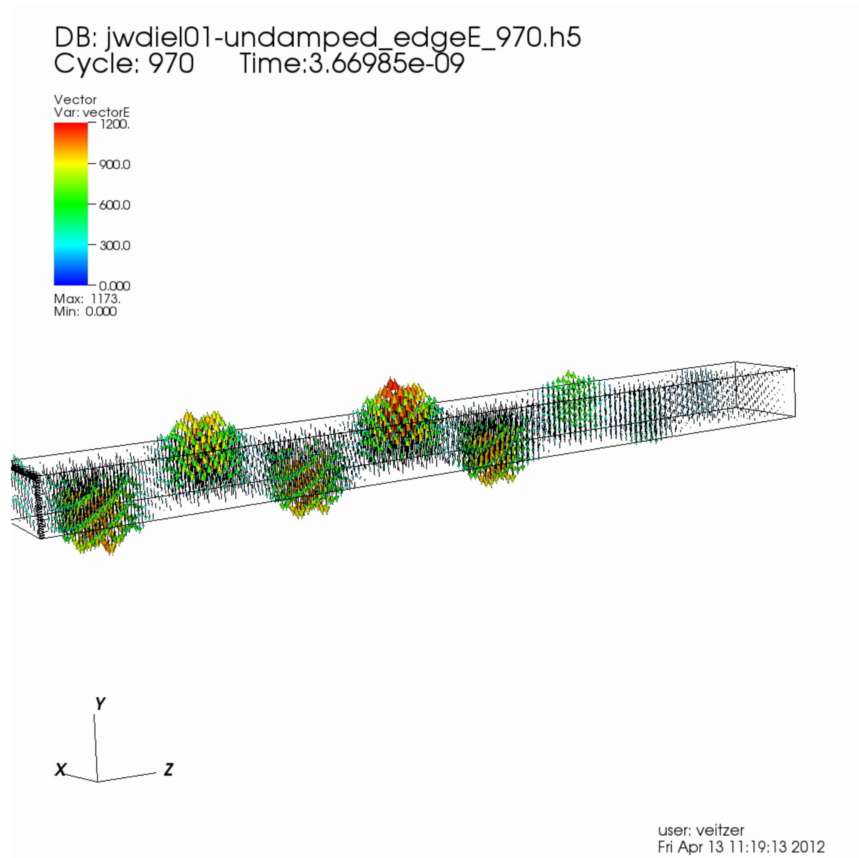

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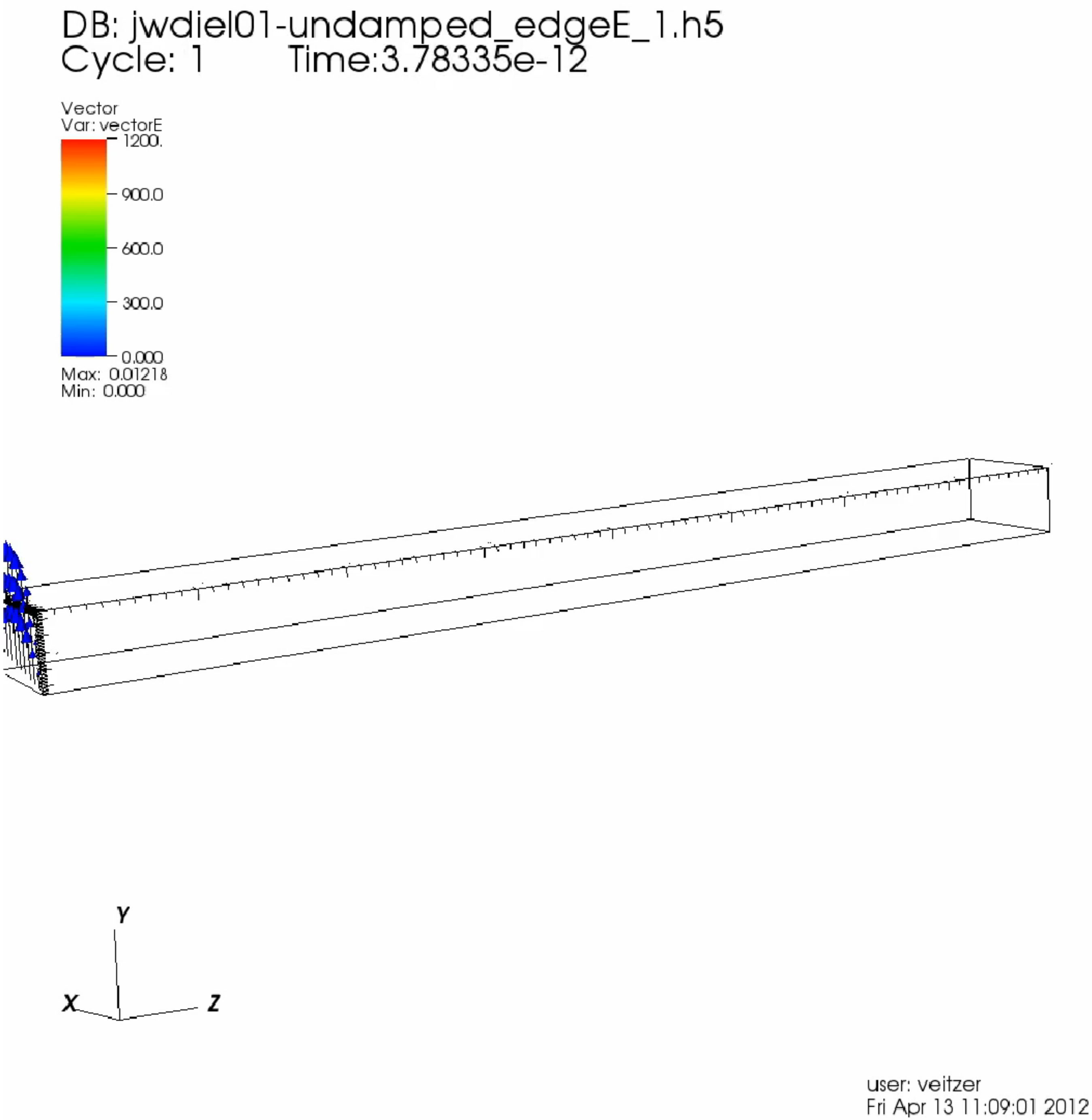
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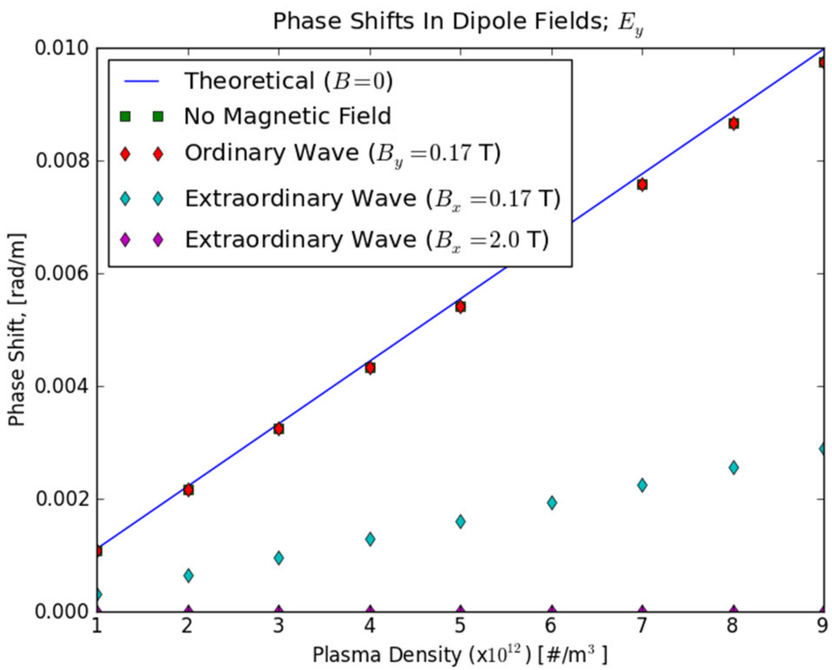
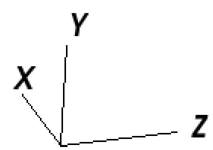
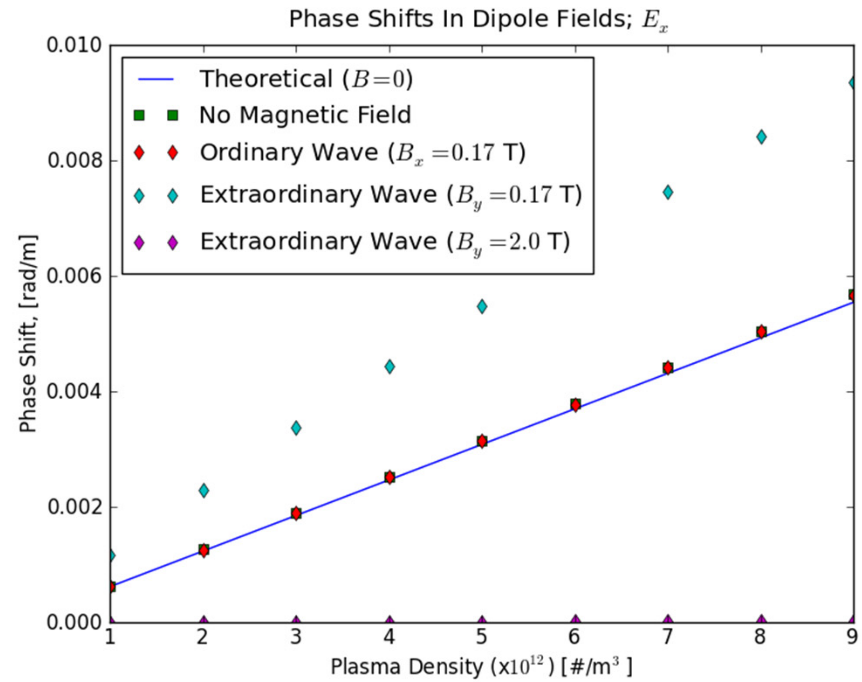
Fri Apr 13 11:09:01 2012

Results 1: Cyclotron Resonances



F_{co} = 1.66 GHz
$B_{resonance}$ = 0.06 T



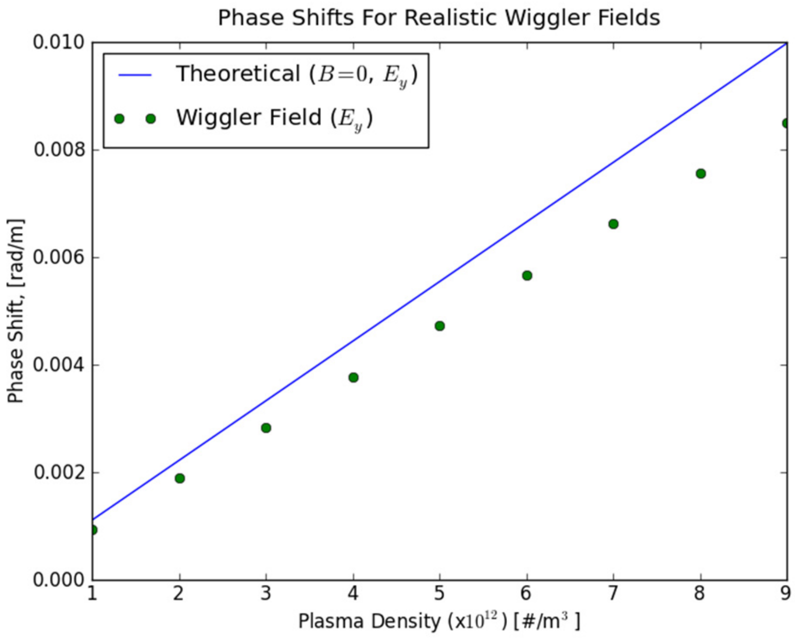


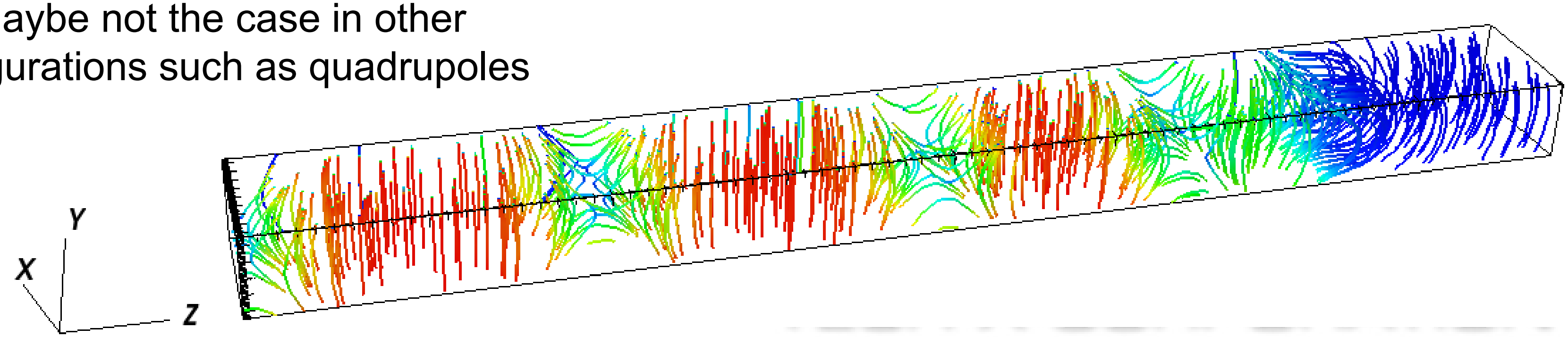
F_{co} = 3.00 GHz
$B_{resonance}$ = 0.11 T

- Phase shift is linear in plasma density
- Ordinary wave does not show any resonant effect for any strength field
- Extraordinary wave is resonant when rf frequency is close to electron cyclotron frequency, but phase shifts are suppressed for higher field strengths

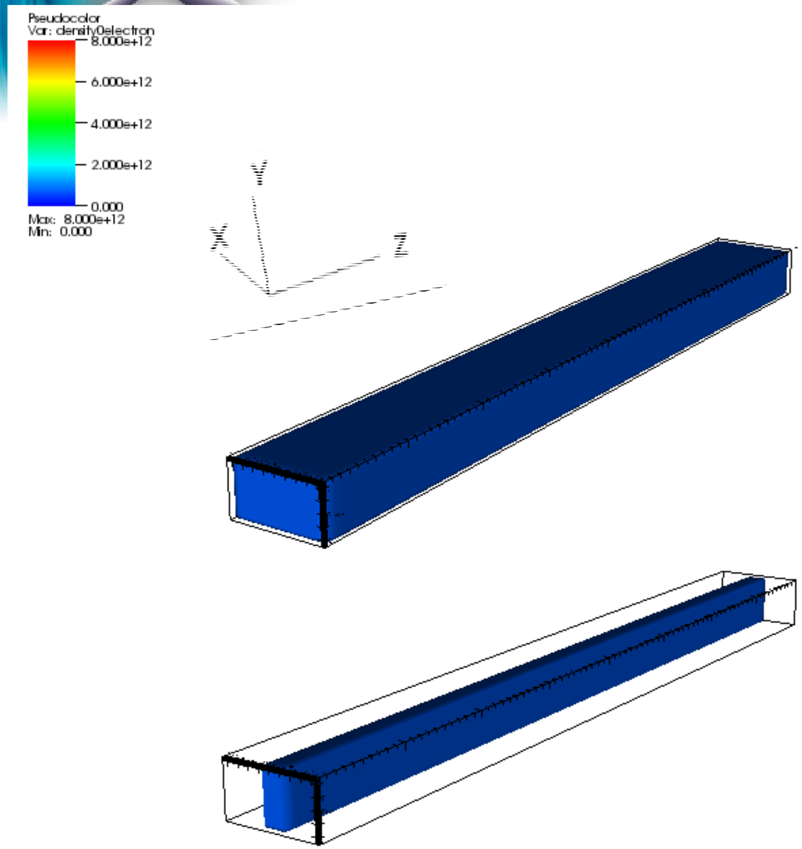
Results 2: Wiggler Magnetic Fields

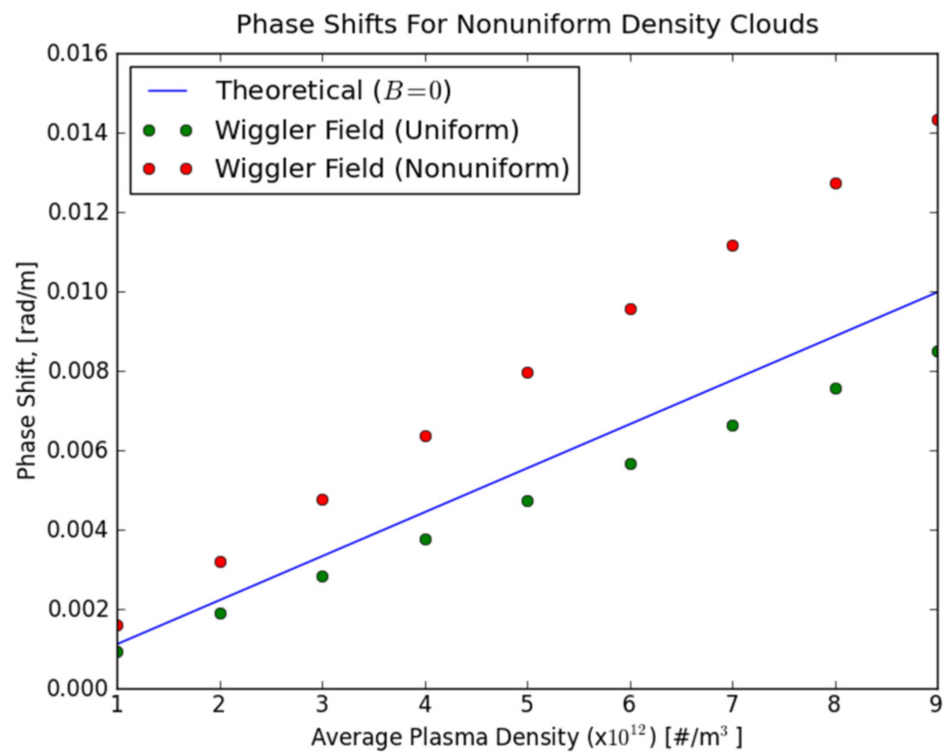
- Phase shifts are linear in plasma density
- Phase shifts are about 20% lower than no magnetic field case
- Would expect essentially O-wave result, because strongest fields are parallel to rf polarization
- Generally this is always going to be the case in wigglers for lowest order TE modes
    - The lowest cutoff frequency is for rf polarized in the shortest transverse direction
    - Strongest B fields will be aligned in this direction as well because of magnet geometries
- But maybe not the case in other configurations such as quadrupoles





Results 3: Nonuniform Density





- Decrease volume by a factor of 4, but increase the density by a factor of 4 as well. *So electron density integrated over entire waveguide is the same*
- Phase shifts are linear in plasma density
- Phase shifts are increased above the nominal value based on integrated plasma density, but much less than expected based on peak density

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Conclusions and Conjecture

- Spatially uniform plasma density produces phase shifts that are linear with density, regardless of magnetic field configuration
- Uniform dipole magnetic fields have the potential to significantly decrease or increase phase shifts depending on the strength and orientation of the fields. Cyclotron resonances may even be desired to increase the signal strengths in certain cases
- Wiggler fields show significant deviation from nominal zero-field case, and can not be replaced by a equivalent dipole field in the strong direction
- From geometric considerations the rf polarization is typically aligned with the strongest wiggler field direction, so cyclotron resonances are not expected in wigglers as expected
- Strong wiggler fields are likely to produce non-uniform cloud densities, that are more likely to enhance phase shifts
- **Conjecture:** If there exists isolated regions of magnetic field in which a resonance occurs, it may be that the upper hybrid wave is cutoff outside of this region (e.g. when the magnetic field is parallel to the wave vector k). In this case wave energy will be trapped in that region, leading to localized electron cyclotron resonance heating (ECRH), which is likely to lead to localized increased cloud density in those regions
- **Thank you!**