NSTX

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Full-Wave Codes Applied to Reflectometry Measurements of Core-Edge Turbulence in NSTX

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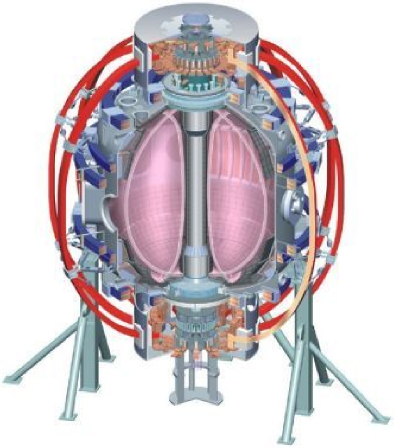

Poster Content

- Abstract
- Introduction
- Description of microwave diagnostics on NSTX.
- Synthetic diagnostics using full-wave codes.
  - 2-D finite-difference time-domain (FDTD) method.
- Acceleration of the 2-D FDTD code using general-purpose computing on graphical processing units (GPGPU).
  - Results using the NVIDIA Tesla C870 GPU Computing Processing Board.
- Application to 2-D profiles and geometry on NSTX.
  - Poloidal wavenumber resolution using modeled fluctuations.
  - Comparison with the phase screen model.
- Summary and future work.

Abstract

The interpretation of turbulence properties from reflectometry measurements is often not straightforward and requires full-wave simulations using modeled turbulence and a detailed knowledge of the equilibrium profiles. On NSTX, the unique combination of reflectometry hardware (FM-CW, fixed-frequency, and correlation reflectometers) is well-suited to turbulence measurements in both core and edge plasmas. Here we report on the simulation work required to generate quantitative estimates of turbulence properties (such as turbulence levels, wave-number spectra, decorrelation times, correlation lengths, flow velocities) from these measurements. We focus on the core-edge region near the L-H transition, where the evolution of the turbulence and density profile characteristics are related to the edge transport barrier formation. Simulations will use the UCLA 1-D and 2-D FDTD full-wave codes. Recently these codes were upgraded to utilize the parallel processing capabilities of the NVIDIA C870 GPU card.

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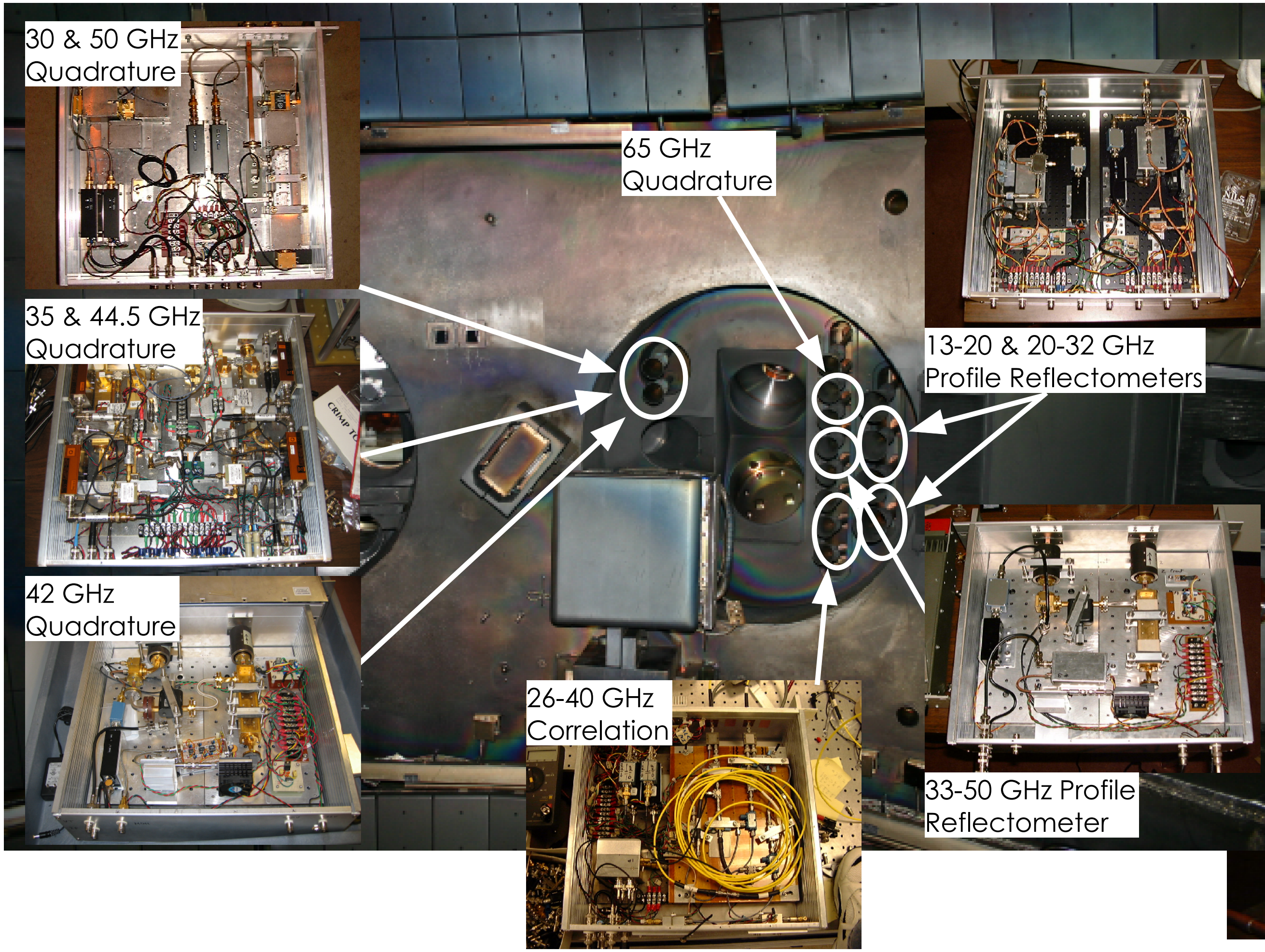
Introduction

- Understanding micro-turbulence is a necessary step to controlling transport in fusion plasmas:
  - Instabilities cover a large range of wavenumbers and frequencies (GAMs, streamers, blobs, ITG, TEM, micro-tearing, ETG).
  - Some instabilities can feed back to the modify the equilibrium profiles (density, temperature, flows, etc.).
- New microwave diagnostics on NSTX enhance our ability to make detailed turbulence and profile measurements.
  - Ultra-fast swept FMCW reflectometers coupled with new analysis techniques:
    - > Electron density profiles with 7 μs time resolution
    - > Sub-millisecond turbulence radial correlations
    - > High-k_r back-scattering
  - Poloidal correlation reflectometer:
    - > Turbulence flow
    - > Poloidal correlations
  - 8-channel fixed-frequency reflectometers (available for FY2010):
    - > Detailed profile of turbulence fluctuation level
- Full-wave codes (used as synthetic diagnostics) are necessary to determine the instrument response for each system and technique.

Millimeter-Wave Diagnostics for 2009 Campaign

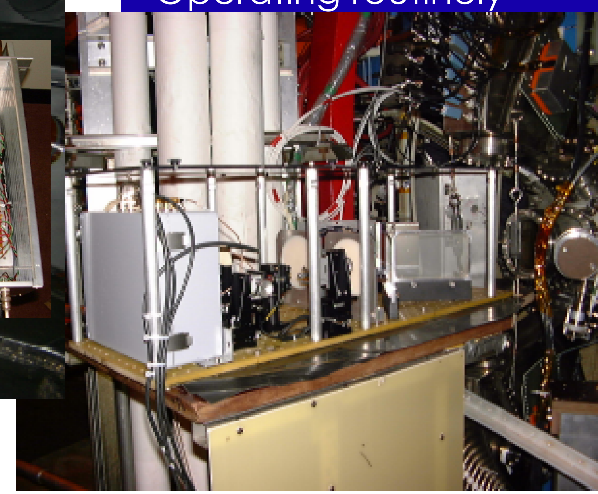


Bay J Reflectometers

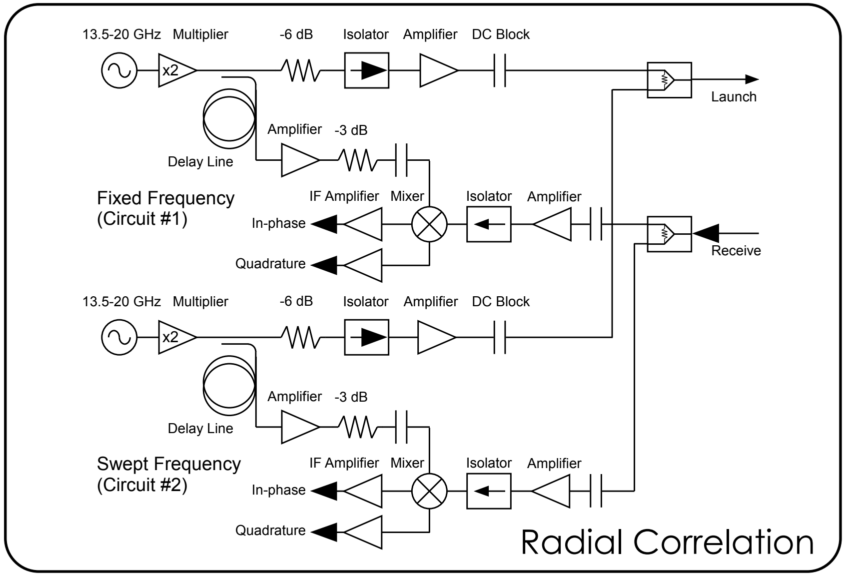
- Fluctuation levels
- Spectra
- Profiles

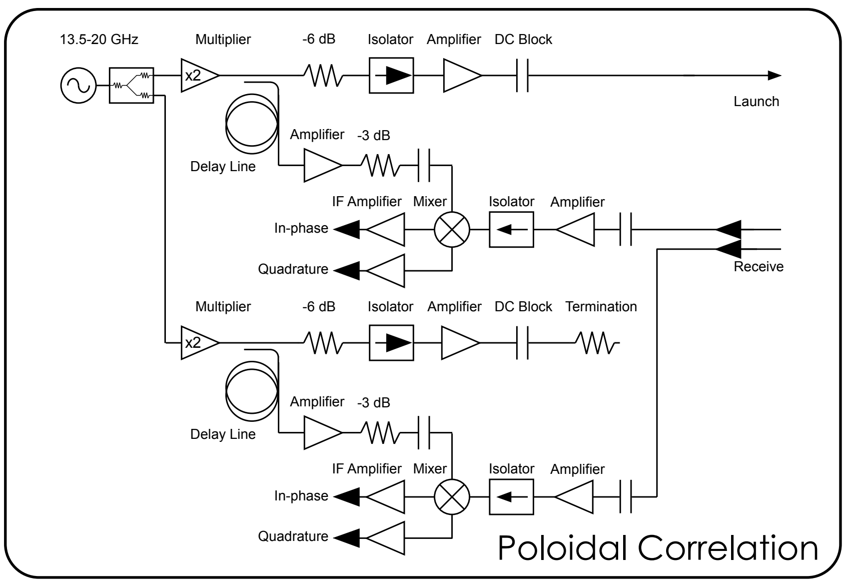
Bay G Interferometer

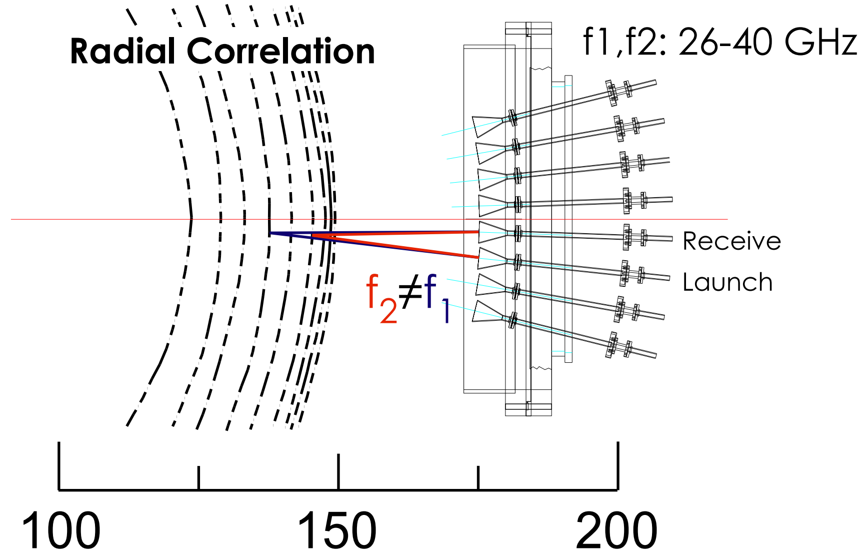
- Radial line density
- Operating routinely

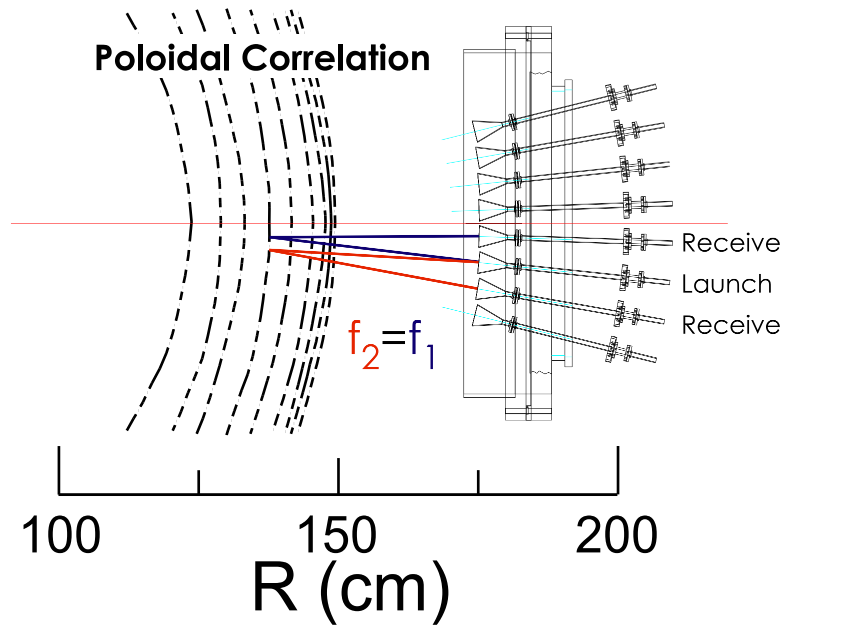


Radial & Poloidal Correlation Reflectometers

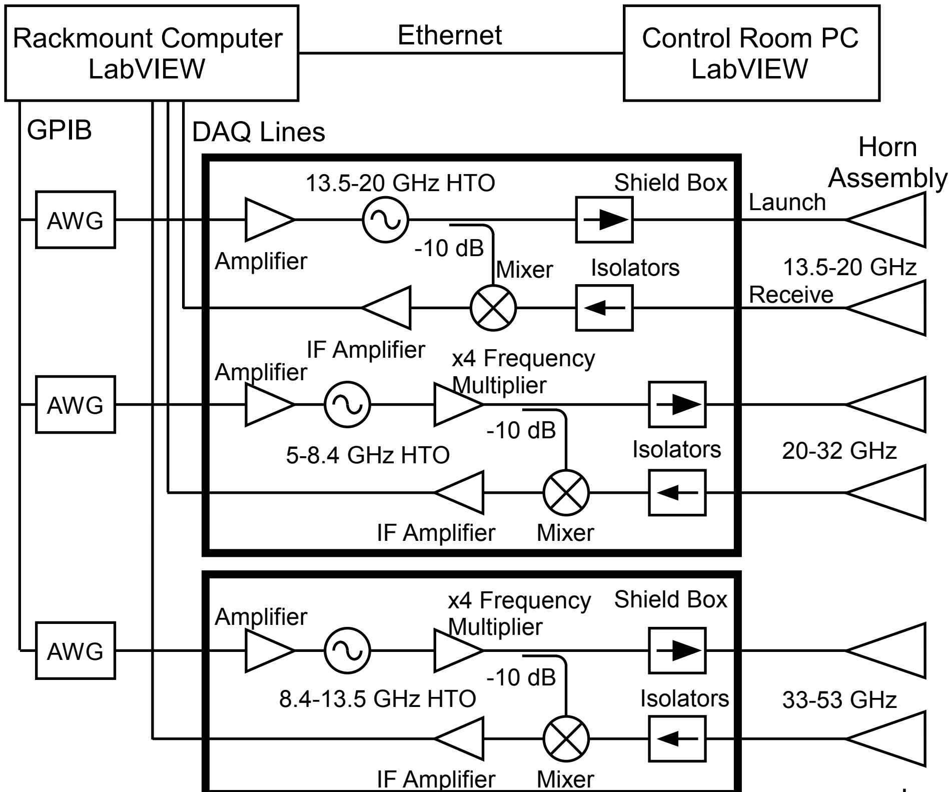


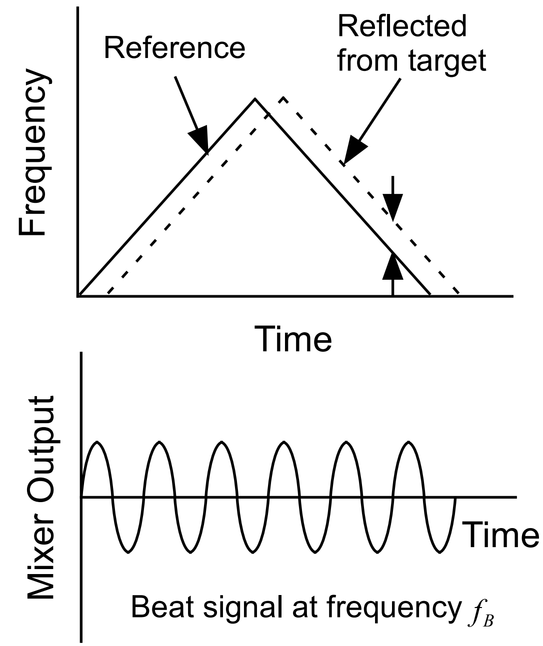


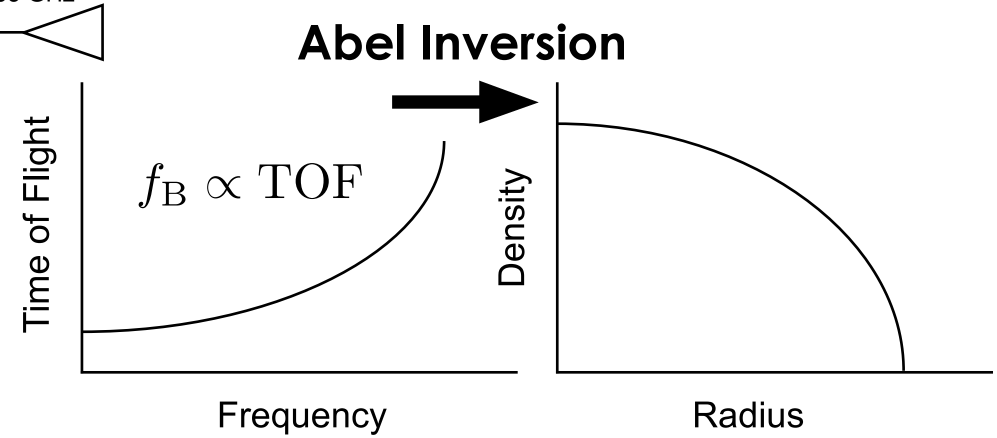




Upgraded FMCW Reflectometer (t_{sweep}<7 μs)







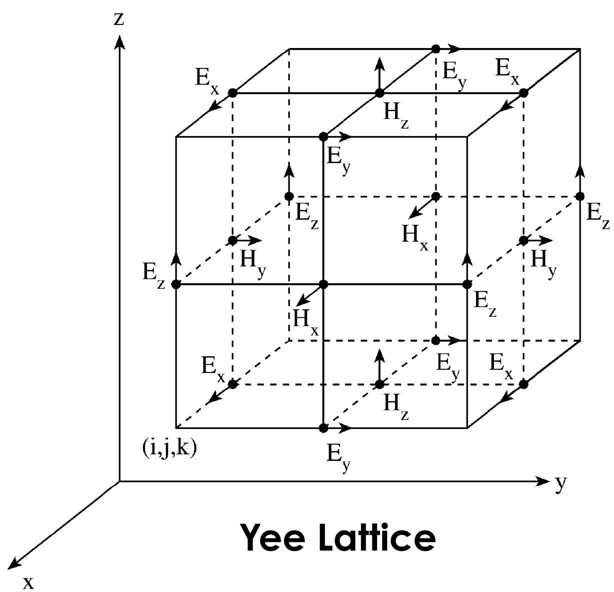
- 13-53 GHz coverage (2.1x10^{12} to 3.5x10^{13} cm^{-3}).
- Maximum repetition rate of 7 μs/swp (12945 total profiles per shot).
- Using spline fit to Thomson edge profile below n_e=9x10^{11} cm^{-3}.

Why Are Full-Wave Codes Necessary?

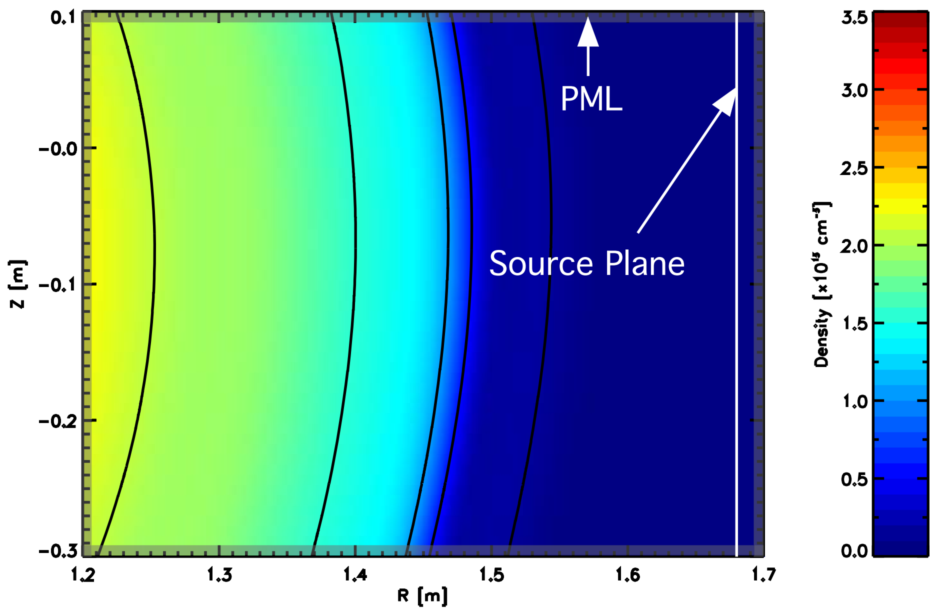
- **Electron density (and magnetic) fluctuations influence the forward and backward propagating beams:**
  - Forward scattering
  - Backward scattering
  - Beam refraction
  - Cross-polarization effects
- **Destructive interference at the receive antenna:**
  - Amplitude modulation
  - Phase corruption
  - Doppler shifts
- **Codes and models exist to evaluate some of these effects:**
  - 1-D full-wave codes for scattering along beam path by radial wavenumbers
  - Models for 2-D diffraction effects (phase screen model) by poloidal wavenumbers
  - 3-D geometric optics codes for beam propagation, refraction and polarization
- **2-D full-wave codes can reproduce all of these effects:**
  - Need a time-domain "Maxwell" solver to reproduce everything.

2-D Finite-Difference Time-Domain Code

- **UCLA 2-D FDTD Code**
  - TE_y(X-mode), TM_y(O-mode), TEM_y (O- & X-mode, R- & L- wave) versions
  - J-E convolution method for current update equations
  - Low-order (central difference) scheme used here
  - Convolutional PML (perfectly-matched layer) boundary conditions
  - TF/SF (total-field/scattered-field) formulation for source excitation (2-D Gaussian beam)
  - Originally based on Microwave Diagnostic Simulator code by H. Hojo



Yee Lattice



2-D Equations for Cold Plasma

- **Reduction to 2-D scalar equations assuming** d/dy=0:

$$\frac{\partial B_x}{\partial t} = \frac{\partial E_y}{\partial z}$$
$$\frac{\partial B_y}{\partial t} = -\left(\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x}\right)$$
$$\frac{\partial B_z}{\partial t} = -\frac{\partial E_y}{\partial x}$$

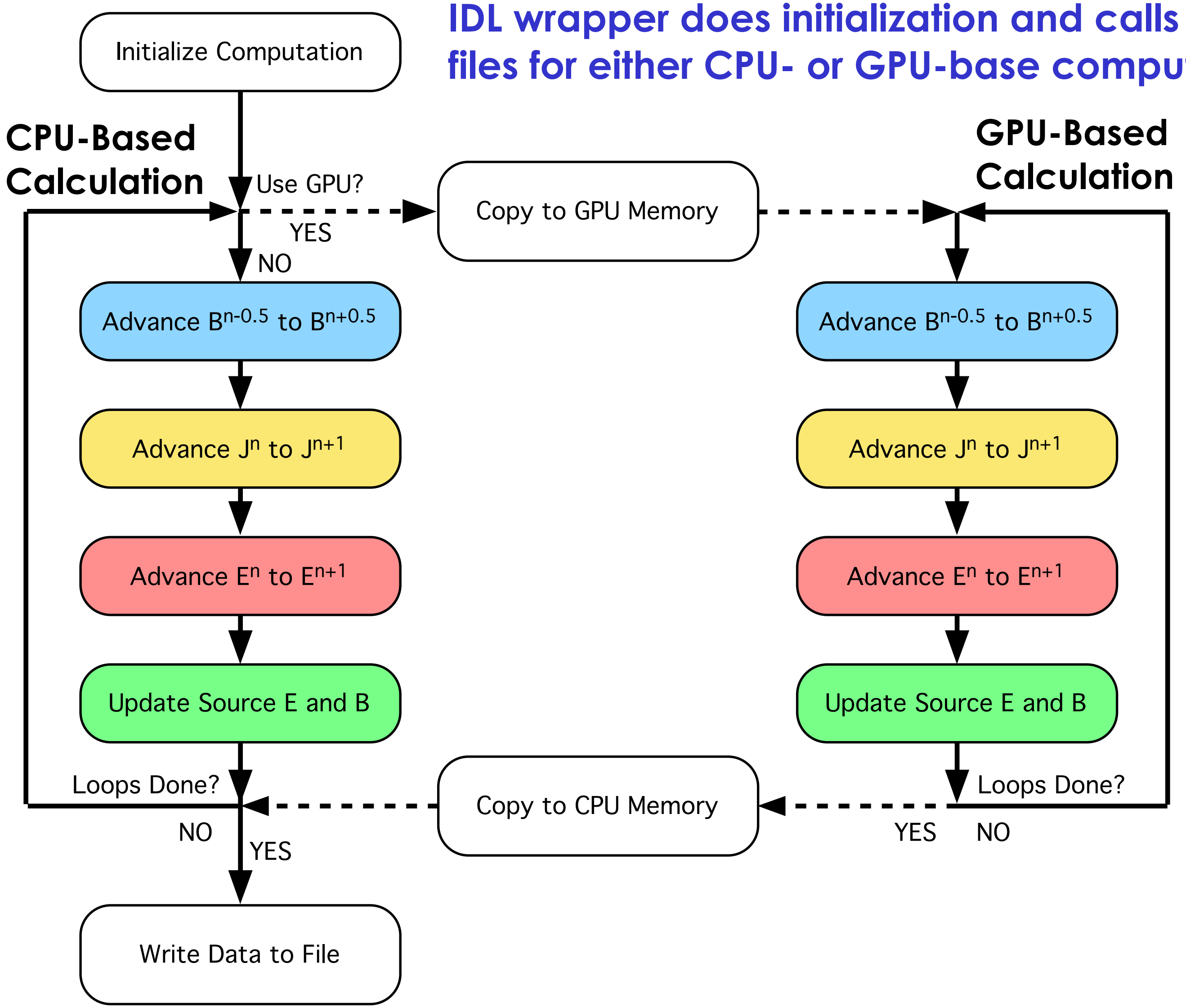
$$\frac{\partial E_x}{\partial t} = -\frac{\partial B_y}{\partial z} - J_x$$
$$\frac{\partial E_y}{\partial t} = \left(\frac{\partial B_x}{\partial z} - \frac{\partial B_z}{\partial x}\right) - J_y$$
$$\frac{\partial E_z}{\partial t} = \frac{\partial B_y}{\partial x} - J_z$$

$$\frac{\partial J_x}{\partial t} = -\nu J_x + f E_x + \alpha J_z b_y - \alpha J_y b_z$$
$$\frac{\partial J_y}{\partial t} = -\nu J_y + f E_y - \alpha J_z b_x + \alpha J_x b_z$$
$$\frac{\partial J_z}{\partial t} = -\nu J_z + f E_z - \alpha J_x b_y + \alpha J_y b_x$$

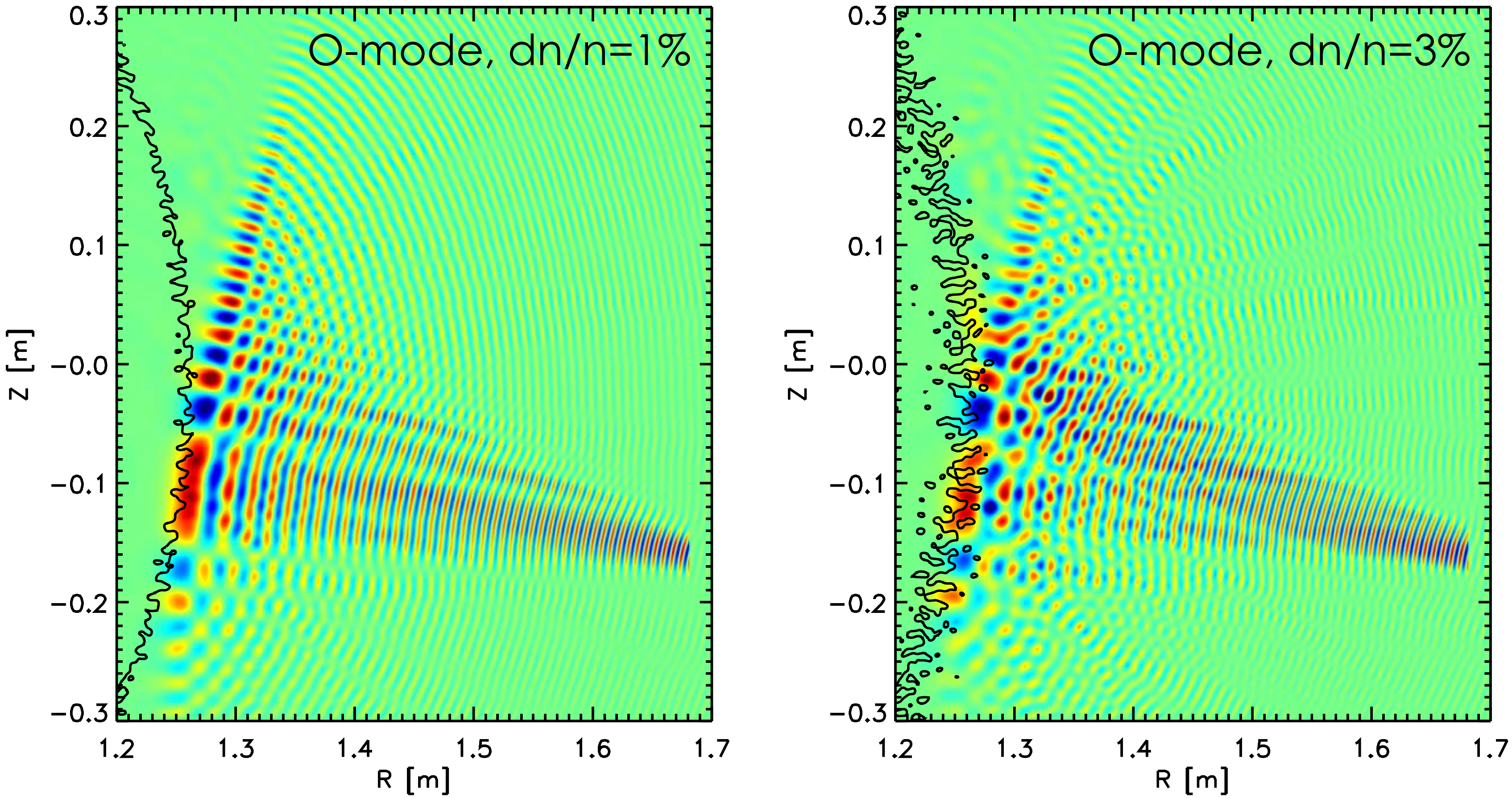
- **Further assumption of b_x=b_z=0 allows decomposition into two sets of equations for TE_y (X-mode) and TM_y (O-mode). TEM_y (O-, X-modes, R- and L-waves) version of code includes all equations and terms.**

Computational Flow Chart

IDL wrapper does initialization and calls shared object files for either CPU- or GPU-base computation.



Beam Scattering Due To Turbulence

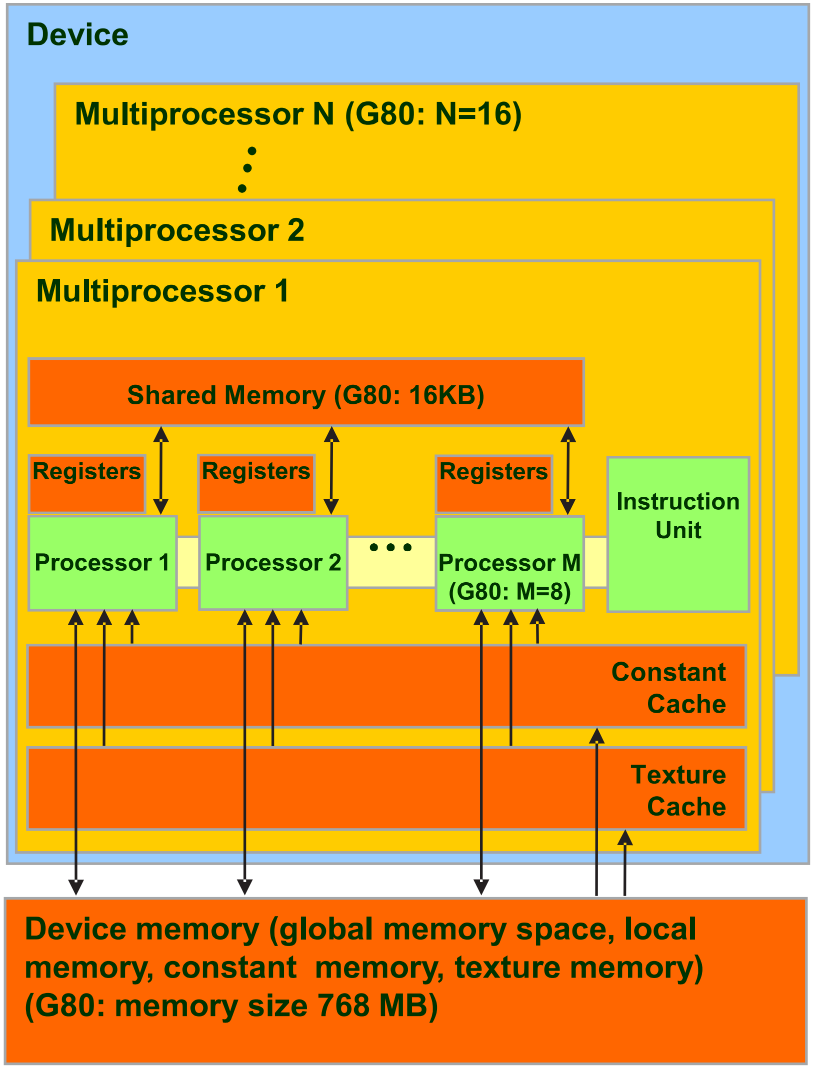


- **68 minutes required on a single CPU core for each simulation run**
  - To look at statistical properties of scattered signal we need hundreds of runs for each ensemble.
  - Need to reduce computation time dramatically. Soln: GPU-assisted computing

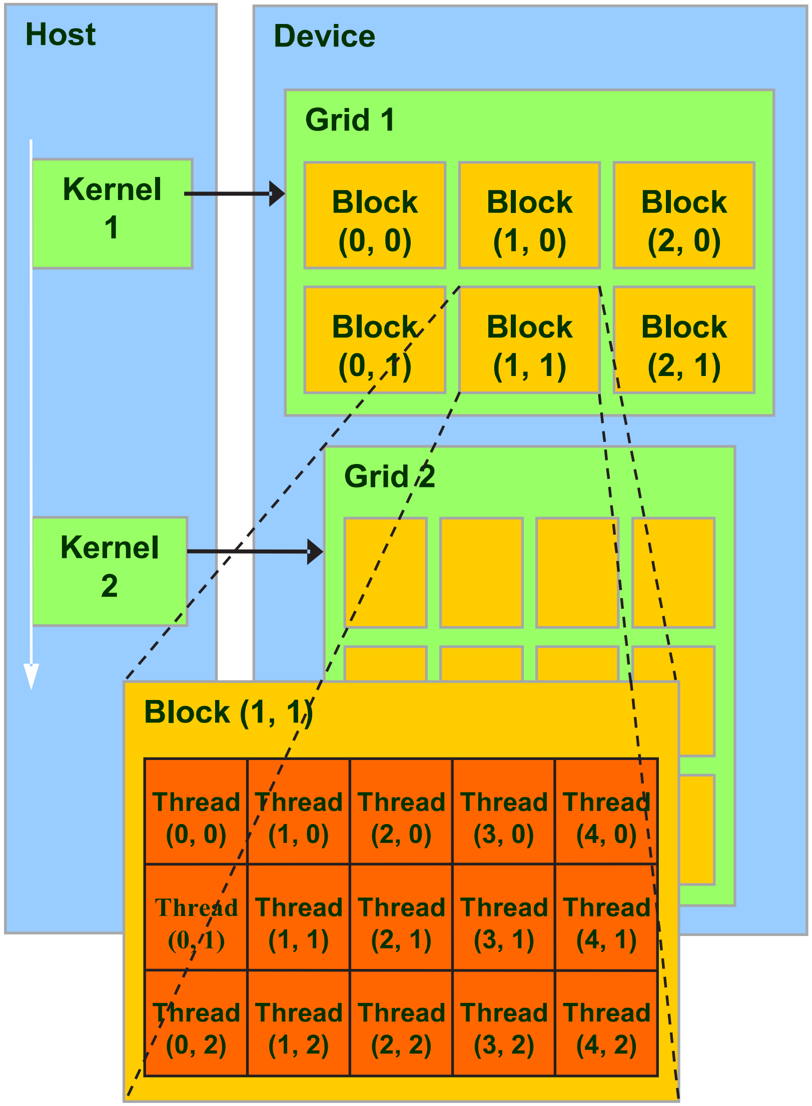
GPGPU Programming

- General-purpose computing on graphics processing units (GPGPU)
  - Utilizes massively parallel architecture of GPU cards
- Examples below with NVIDIA Tesla C870 GPU Computing Board
  - 128 streaming processor cores (16 multiprocessors)
  - Memory size: 1536 MB
  - Double wide, PCI Express x16
  - Power requirement: 171 Watts
  - Compute capability 1.0
- CUDA for C programming environment
  - Wrapper program in IDL for loading inputs
  - Shared library for compiled kernel programs called from IDL
- Significant acceleration of computation speed
  - x20 acceleration for typical X-mode computation
  - x15 acceleration for typical O-mode computation
- Further details in Poster JP8.00017 "GPU-Accelerated FDTD Full-Wave Codes for Reflectometry Simulations", B. C. Rose et al.

GPGPU Architecture



Source: nVidia, 2007.

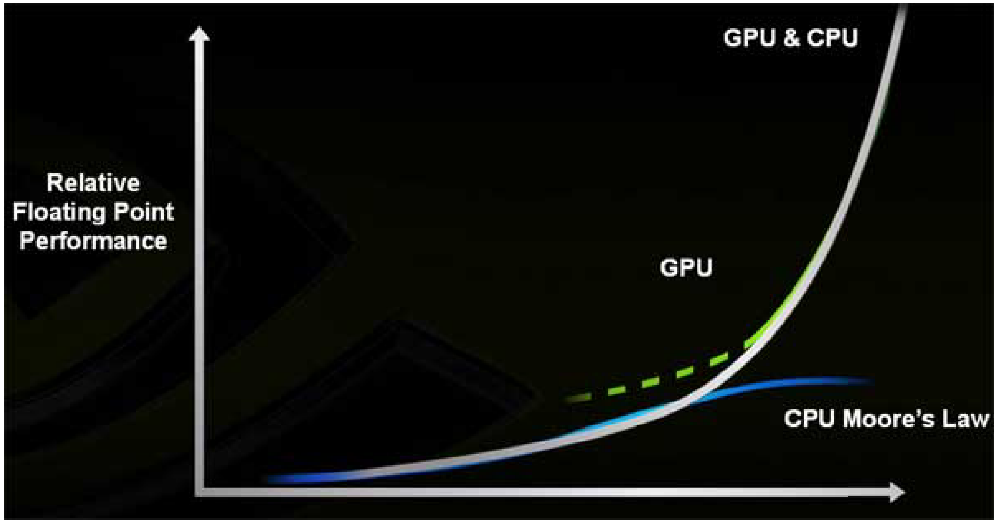


Computation Hardware

- **Hardware**
  - Host system: Dell T7500n Desktop Workstation
  - CPU: Dual Quad-Core Intel Xeon E5530 2.4 GHz
  - Memory: 12 GB DDR 1066 MHz ECC
  - NVIDIA Tesla C870 GPU Computing Processing Board
- **Software**
  - Red Hat Enterprise Linux WS v5.3 (64-bit)
  - GCC 4.1.2
  - CUDA 2.3 for Linux

Future of GPGPU Computing

- **GPU computing is necessary for high performance computing**
  - CPU's: diminishing returns in computing performance per transistor number
  - GPU's scaling well beyond Moore's law in performance



- **Next generation GPU architecture from NVIDIA: "Fermi"**
  - Expected to arrive in Q1 2010
  - Estimated acceleration over CPU: x100?
  - 6 GB of memory: 3-D geometries possible?

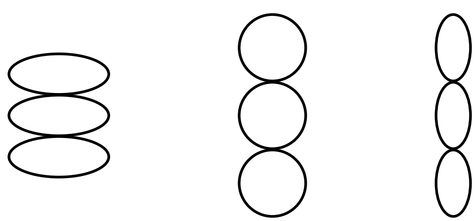
Fluctuation Model for k_θ Response

- **Fluctuation Model:**
  - Time-varying sinusoids with the following spatial structure (max 1% fluctuation):

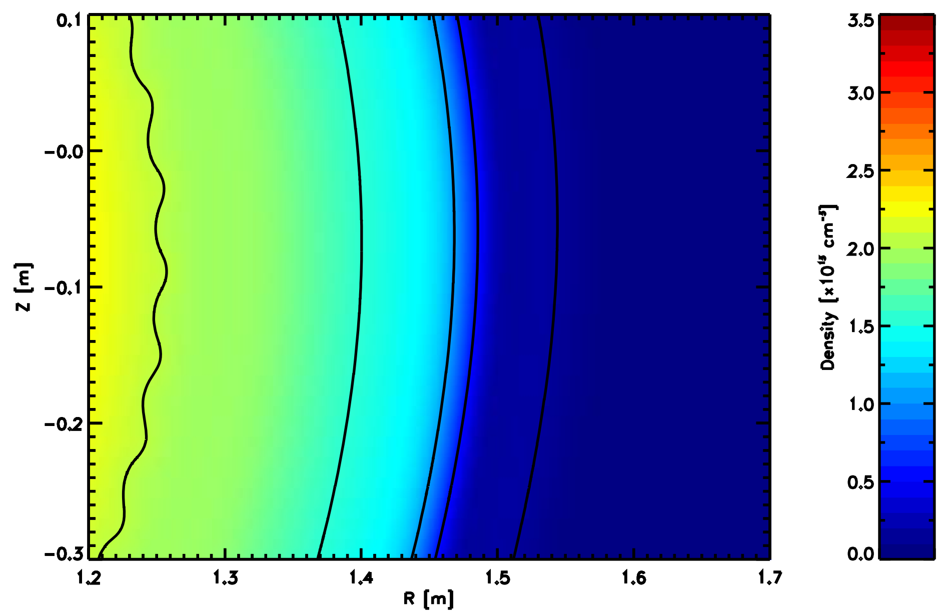
$$\frac{\delta n(r,\theta)}{n} = 0.01\cos(k_\theta R_c \theta)\exp\left[-\frac{(r-r_0)^2}{\Delta r^2}\right]$$

    - > Poloidal wavenumber: k_θ
    - > Cutoff surface curvature: R_c
    - > Poloidal coordinate: θ
    - > Radial coordinate: r
    - > Cutoff radius: r_0
    - > Perturbation scale length: Δr

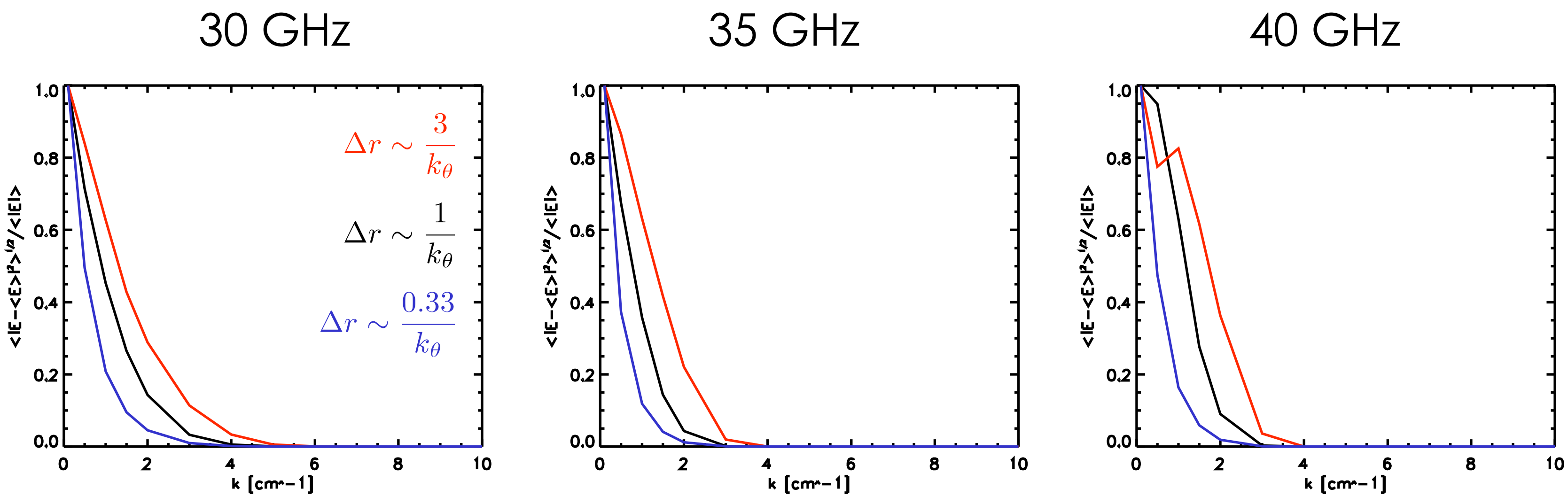
$$\langle k_r \rangle = \sqrt{\frac{2}{\pi}}\frac{1}{\Delta r}$$



$\Delta r \sim \frac{3}{k_\theta}$ $\quad$ $\Delta r \sim \frac{1}{k_\theta}$ $\quad$ $\Delta r \sim \frac{0.33}{k_\theta}$

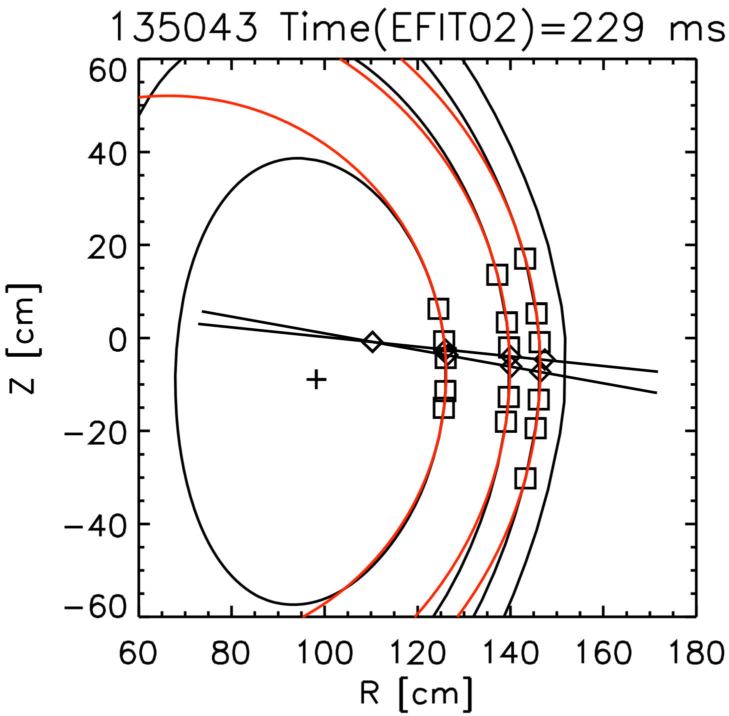


Simulation Results for k_θ Scan



- ~2 days using single GPU
  - Approximately 800 individual runs.
- Monotonic k spectral response

Comparison With Phase Screen Model

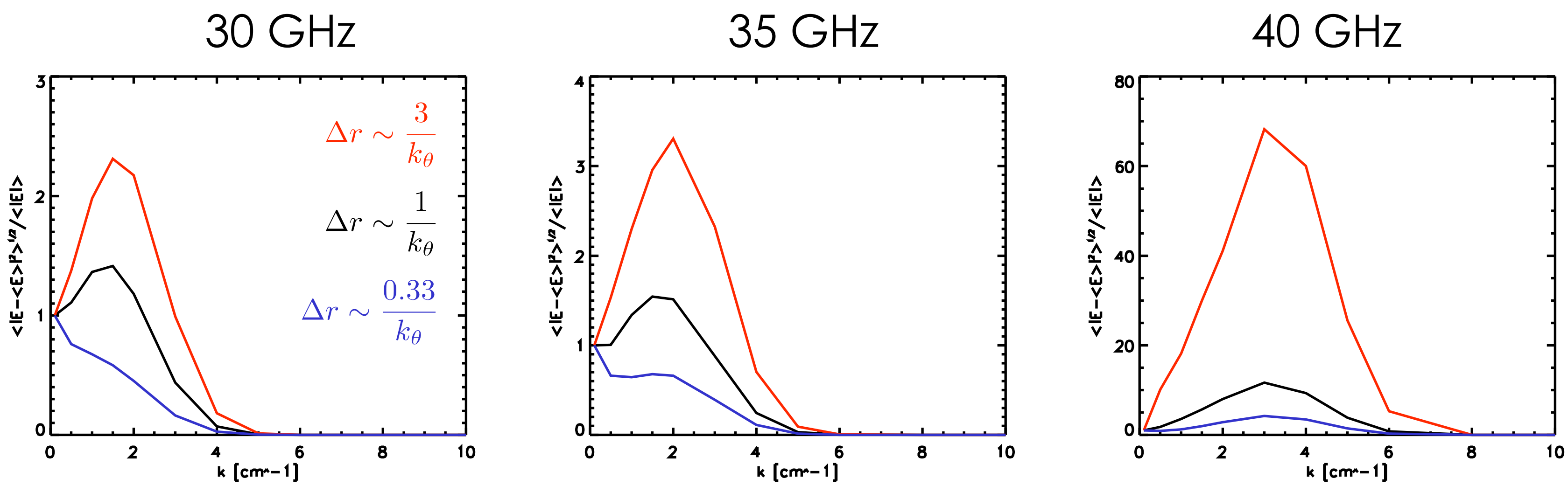


Rmid Cutoff: Cutoff surface mapped to midplane radius.
rw: Distance along bisector from cutoff to horns.
zw: Vertical horn offset from bisector.
zs: Upward shift of contour circles.
w(z): G.B. width at cutoff.
R: Beam radius of curvature at cutoff.
Rz: Plasma radius of curvature (poloidal)
Rx: Plasma radius of curvature (toroidal)
theta: Launch angle from horizontal.

Frequency [GHz]	Rmid Cutoff [cm]	rw [cm]	zw [cm]	zs [cm]
30.000000	146.19633	26.636741	2.3395906	-13.040540
35.000000	139.57169	33.940484	2.3677450	-12.846563
40.000000	125.65396	48.479160	2.4003493	-12.910556

Frequency [GHz]	w(z) [cm]	R [cm]	Rz [cm]	Rx [cm]	theta [deg]
30.000000	3.5300755	30.763628	88.977955	146.96559	2.0920282
35.000000	3.8504259	38.140340	79.333656	140.45998	2.0920282
40.000000	4.7817685	52.094388	59.794524	126.80483	2.0920282

Phase Screen Results



- **Strong Doppler enhancement due to large misalignment.**
  - Plasma center shifted downard ~10 cm.

Summary

- Significant speed-up of 2-D full-wave reflectometry codes by using GPU-assisted computing:
  - x15-20 acceleration
  - Computation run time of a few minutes instead of hours
- Reflectometer response for k_θ scans using antennas 9 and 10 and equilibrium from NSTX shot 135043
  - Initial batch of ~800 runs (2-days)
  - 30, 35 and 40 GHz cases
  - Fluctuation model with various k_r to k_θ ratios
- Simple comparison with phase screen model
  - Phase screen model shows strong Doppler enhancement due to large plasma shift
  - 2-D full wave results show no Doppler enhancement

Future Work (Code Applications)

- Continue evaluation of reflectometer response to turbulence
  - Map out response to radial wavenumbers
    - > Vary radial correlation lengths and fluctuation level
  - Apply code to modeled 2-D turbulence targets
  - Target simulation results from BOUT (edge turbulence) and GTC (core turbulence)
    - > Connection between experiment and theory
- Time-varying sources
  - Broadband and pulsed waveforms
    - > Synthetic diagnostic for FMCW reflectometers
- Time-varying targets
  - Poloidal correlation measurements
    - > Poloidal correlation lengths and flows
  - Doppler reflectometry studies
- Application to other diagnostics
  - UCLA polarimeter available FY2010
    - > 2-D (or 3-D) version of code can be used to evaluate Faraday rotation, Cotton-Mouton and other effects. Can include full physics and fluctuations.
  - Forward, far-forward, and backward scattering methods

Future Work (Code Enhancements)

- 2-D TEM_y coupled full-wave code for the GPU
  - Effects due to magnetic fluctuations and shear (mode conversion, etc.)
  - Application to polarimetry
- Include kinetic modifications to handle relativistic effects in warm or hot plasmas
  - Trivial approximations for decoupled 2-D cases
  - 2-D coupled case not trivial. Vlasov-Maxwell equations
- Extension from to 3-D
  - More realistic estimate of beam propagation, power flow, polarization change, etc.
  - Reasonable computation times may be achievable in near future
- Next generation GPGPU board "Fermi"

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NVIDIA Tesla C870 GPU Computing Board

- **GPU**
  - 128 streaming processor cores
  - Core processor clock speed: 1.35 GHz
  - Voltage: 1.3 V +/- 0.13 V
  - Dimensions: 42.5mm x 42.5mm (1449 FCBGA)
- **Board**
  - 12 layer printed circuit board
  - PCI Express x16 Generation 1 system interface
  - Power: 170.9 W
- **Memory**
  - Memory size: 1536 MB (24 16Mx32 GDDR3 136-pin BGA SDRAM)
  - Memory clock: 800 MHz
  - Interface: 384-bit GDDR3
- **Bios**
  - Serial ROM, 128 K x 8