Three-dimensional Simulations of Electron Beams Focused by Periodic Permanent Magnets

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A fully three-dimensional (3D) model of an electron beam focused by a periodic permanent magnet (PPM) stack has been developed. First, the simulation code MAFIA was used to model a PPM stack using the magnetostatic solver. The exact geometry of the magnetic focusing structure was modeled; thus, no approximations were made regarding the off-axis fields. The fields from the static solver were loaded into the 3D particle-in-cell (PIC) solver of MAFIA where fully 3D behavior of the beam was simulated in the magnetic focusing field. The PIC solver computes the time-integration of electromagnetic fields simultaneously with the time integration of the equations of motion of charged particles that move under the influence of those fields. Fields caused by those moving charges are also taken into account; thus, effects like space charge and magnetic forces between particles are fully simulated [[1]]. The electron beam is simulated by a number of macro-particles. These macro-particles represent a given charge Q amounting to that of several million electrons in order to conserve computational time and memory. Particle motion is unrestricted, so particle trajectories can cross paths and move in three dimensions under the influence of 3D electric and magnetic fields. Correspondingly, there is no limit on the initial current density distribution of the electron beam, nor its density distribution at any time during the simulation.

Simulation results including beam current density, percent ripple and percent transmission will be presented, and the effects current, magnetic focusing strength and thermal velocities have on beam behavior will be demonstrated using 3D movies showing the evolution of beam characteristics in time and space. Unlike typical beam optics models, this 3D model allows simulation of asymmetric designs such as non-circularly symmetric electrostatic or magnetic focusing as well as the inclusion of input/output couplers.

[1] The MAFIA Collaboration, *MAFIA TS3 the 3D-PIC Solver*, December, 1996.

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Summary

- Importance of Efficient Electron Beam Focusing
- Model - Hughes MMPM TWT
- MAFIA model
  - Periodic Permanent magnet (PPM) stack - Static solver
  - Electron Optics model - PIC solver
  - Thermal velocity model
- Investigate
  - Percent ripple
  - Percent transmission
  - Current density
  - Tunnel length

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Electron Beam Focusing

- Excessive growth in beam diameter leads to:
  - backward wave oscillations
  - premature saturation
- Electron beam/RF circuit interception causes:
  - excessive circuit heating
  - decreased efficiency
- These imply serious reduction in tube performance
- 3D Model allows:
  - Asymmetric designs
  - Inclusion of Couplers
  - Input/Output sections
  - More accurate spent beam data for collector design

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Hughes 8916H MMPM TWT

Operating parameters for the Hughes 8916H helical TWT

Frequency (GHz)	18-40
V_o (kV)	7.6
I_o (mA)	81.0
Perveance (10^{-6})	0.12
b/a	0.5

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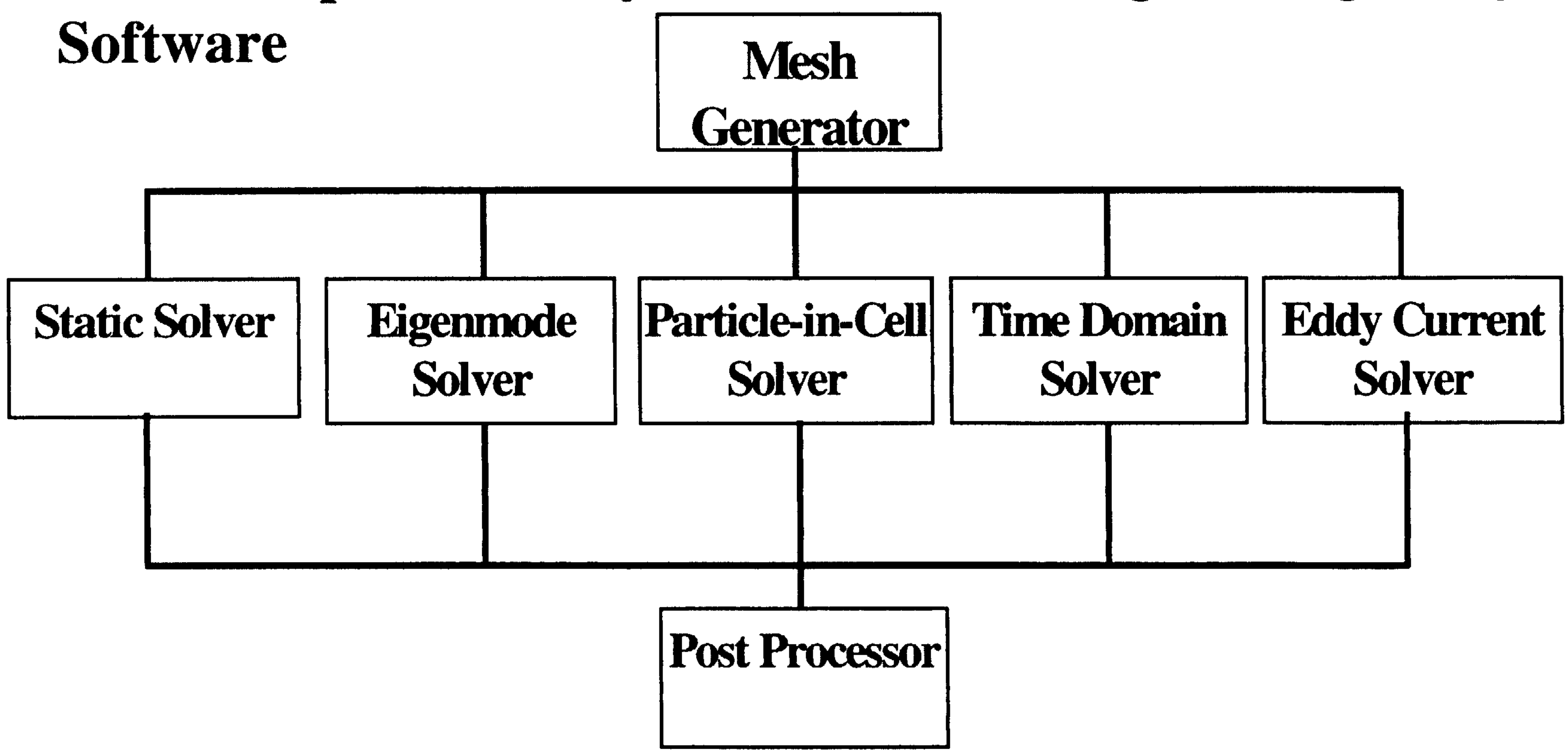
MAFIA Code

- Solution of *MA*xwell's equations by the *F*inite-*I*ntegration-*A*lgorithm
- Three-Dimensional Electromagnetic Particle-in-Cell Simulation Code
- Data Accepted Directly from Standard Engineering Design Software



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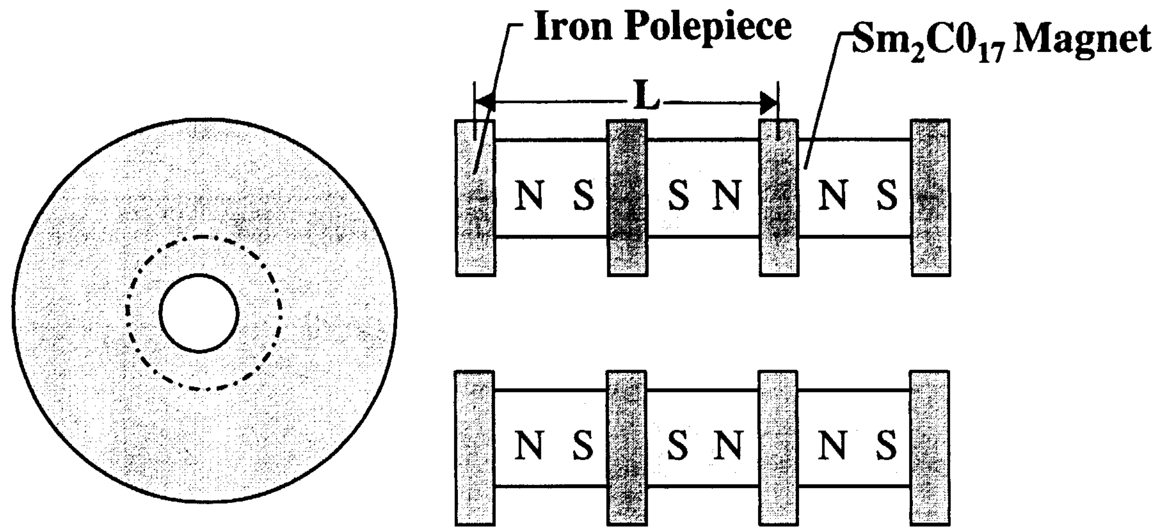
3D PPM Stack Model



Cross-sectional view and top view of PPM stack

Mesh Generator –
Model 3D PPM Stack

Static Solver –
- Define material properties
- Calculate Magnetic flux density, B

- Provided B-H curve used for iron pole pieces
- Fixed magnetization and permeability used for magnets

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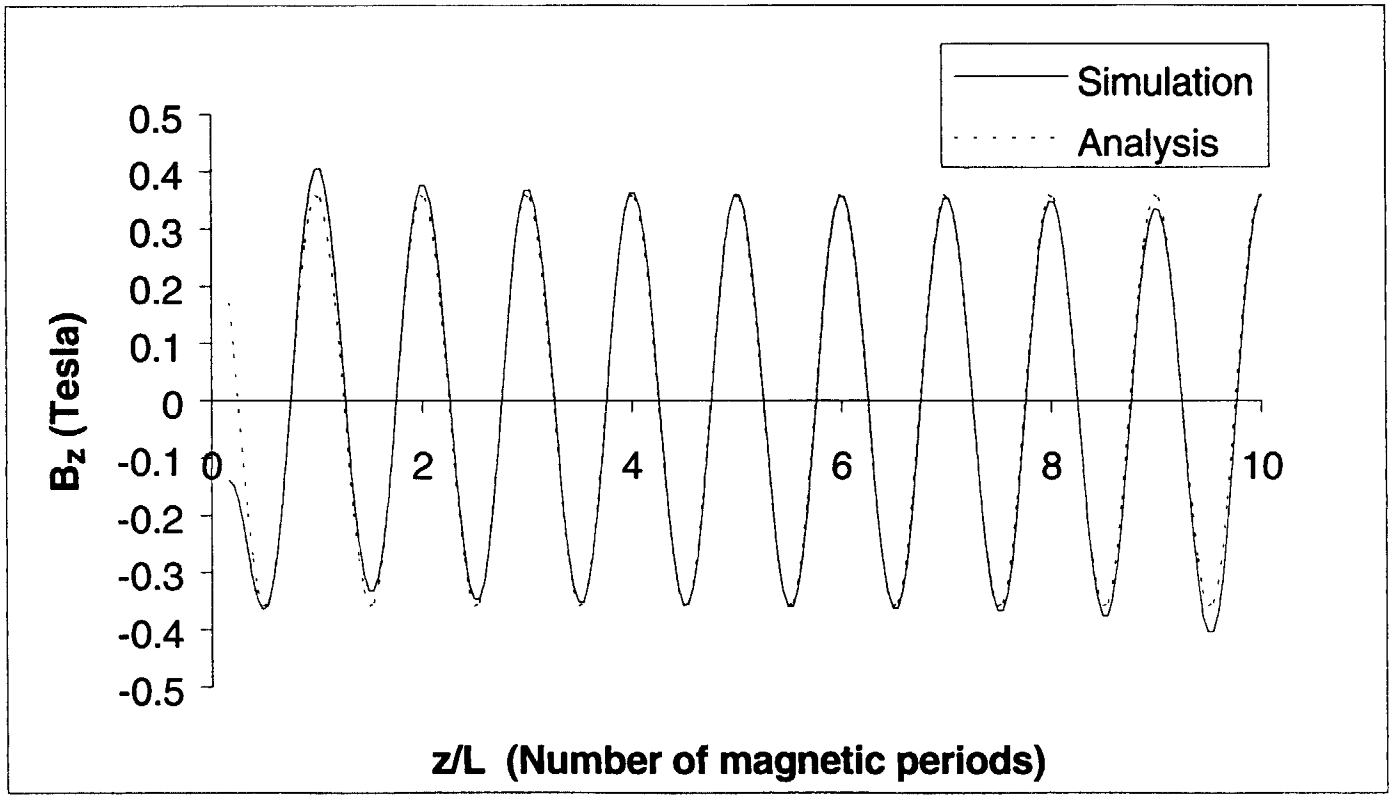
Longitudinal Magnetic Flux Density, Bz



Simulated and analytical longitudinal component of magnetic flux density B_z on the PPM stack central axis versus z/L

3D Electron Optics Model

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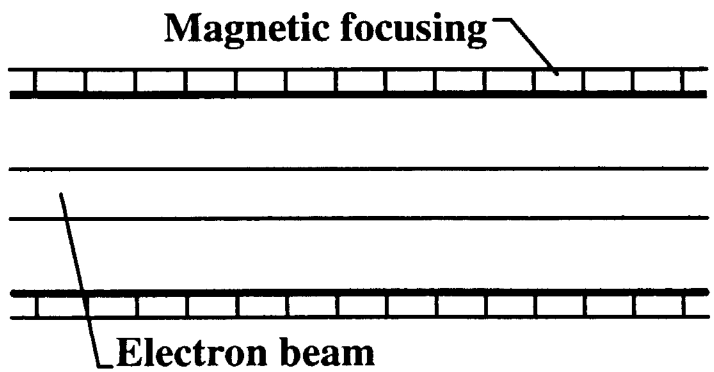
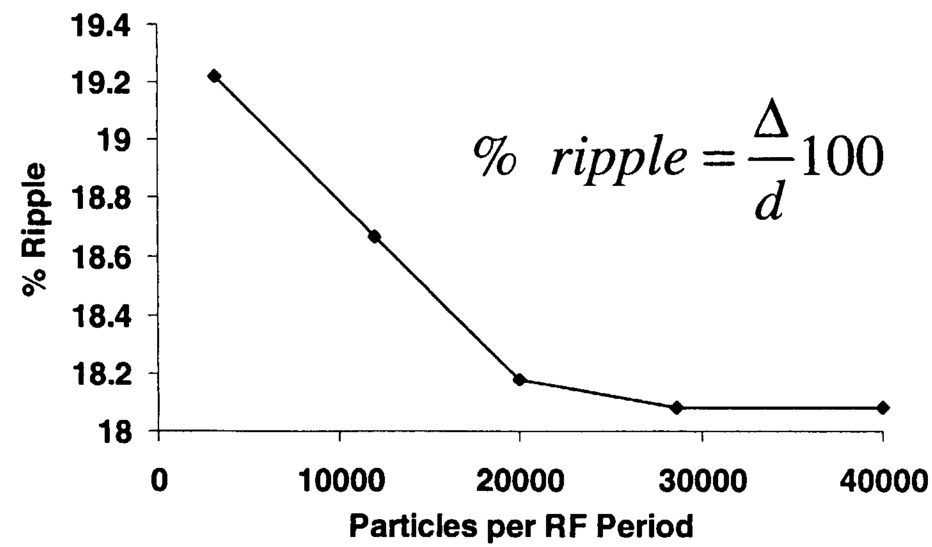


- Electron beam simulated by macro-particles
  - Each amounts to several million electrons
- Particle motion unrestricted
  - Move in 3D under influence of 3D fields
  - No limit on current density distribution or emission direction of electron beam

Mesh Generator - Model 3D beam tunnel

Particle-in-Cell Solver –

- Load B from PPM stack from static solver
- Define material properties
- Define emission properties of electron bunch
- Calculate particle motion under influence of self- and static fields



$$\% \ ripple = \frac{\Delta}{d} 100$$

Percent ripple versus number of particles

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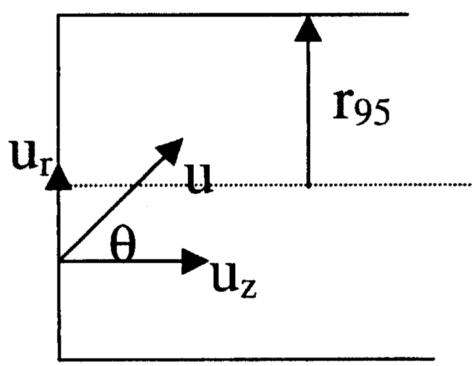
Thermal velocity model



- Radial transverse velocities assumed
- Distribution based on Gaussian probability function with standard deviation

$$\sigma = \frac{r_c}{r_{95}} \sqrt{\frac{kT}{m}}$$

k = Boltzman's constant

m = mass of electron

T = cathode temperature in Kelvin

r_{95} = beam radius containing 95% of beam current

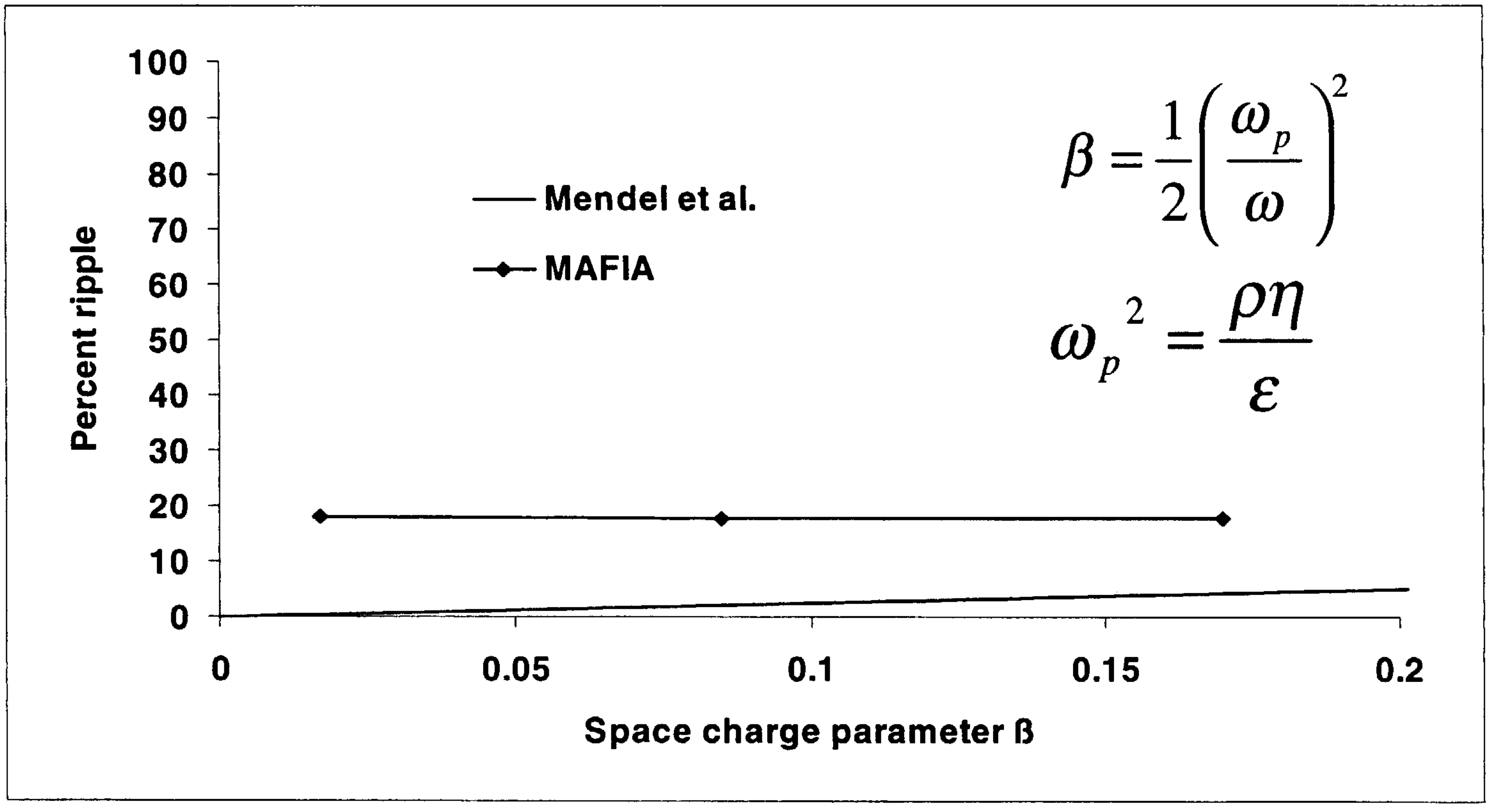
r_c = cathode disk radius

- Ejection angle normal to the emission plane determined by

$$\theta = \tan^{-1}\left(\frac{u_r}{u_z}\right)$$

- Thus, particle trajectories are emitted across beam cross section with random distribution of ejection angle θ according to mentioned Gaussian probability function.

Percent Ripple -Comparison to Mendel et al.



$$\beta = \frac{1}{2}\left(\frac{\omega_p}{\omega}\right)^2$$

$$\omega_p^{\ 2} = \frac{\rho\eta}{\varepsilon}$$

Percent ripple for various values of space charge parameter β at Brillouin focusing

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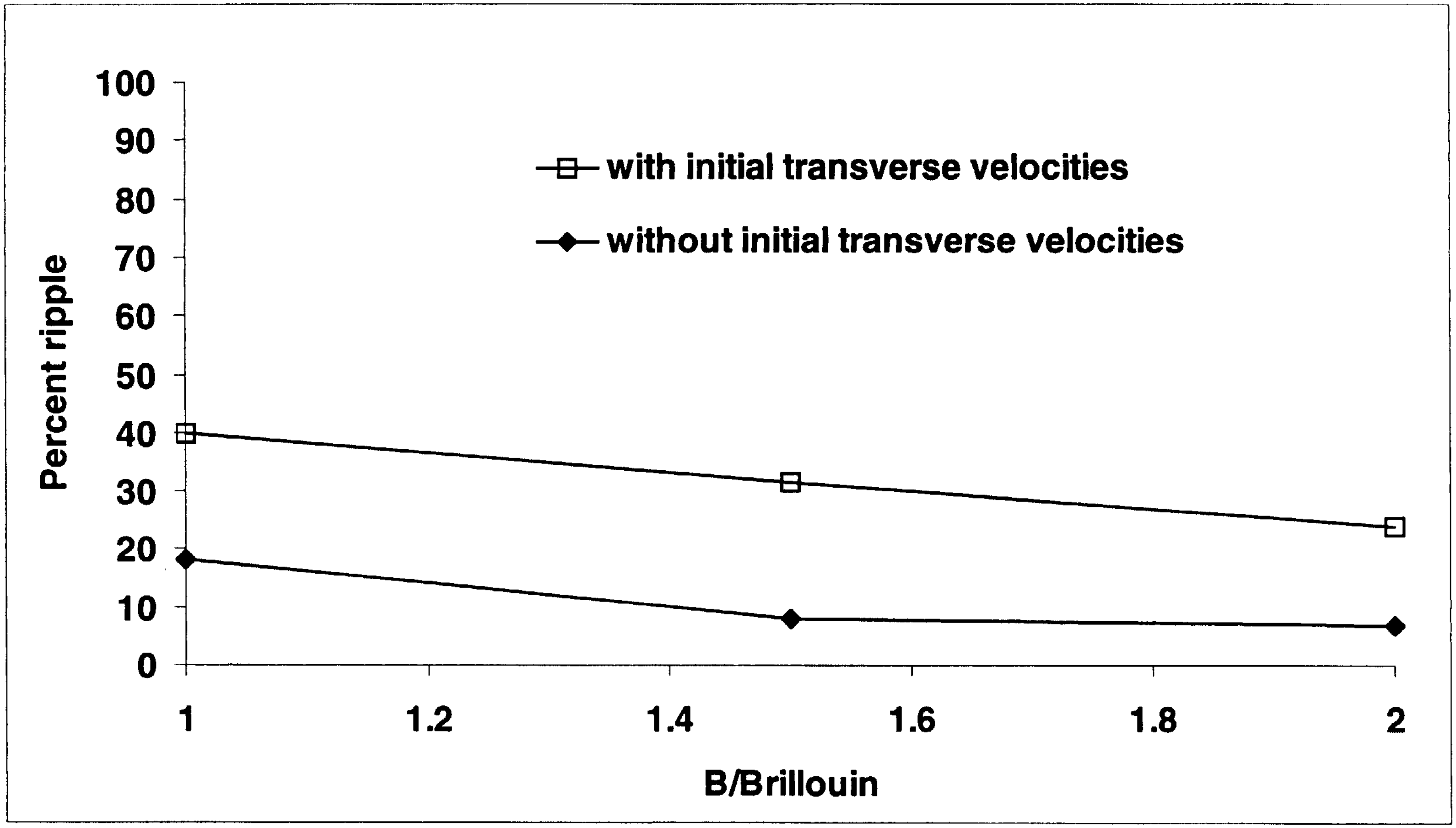
Percent Ripple



Percent ripple for 81mA beam with and without initial transverse velocities using various focusing strengths

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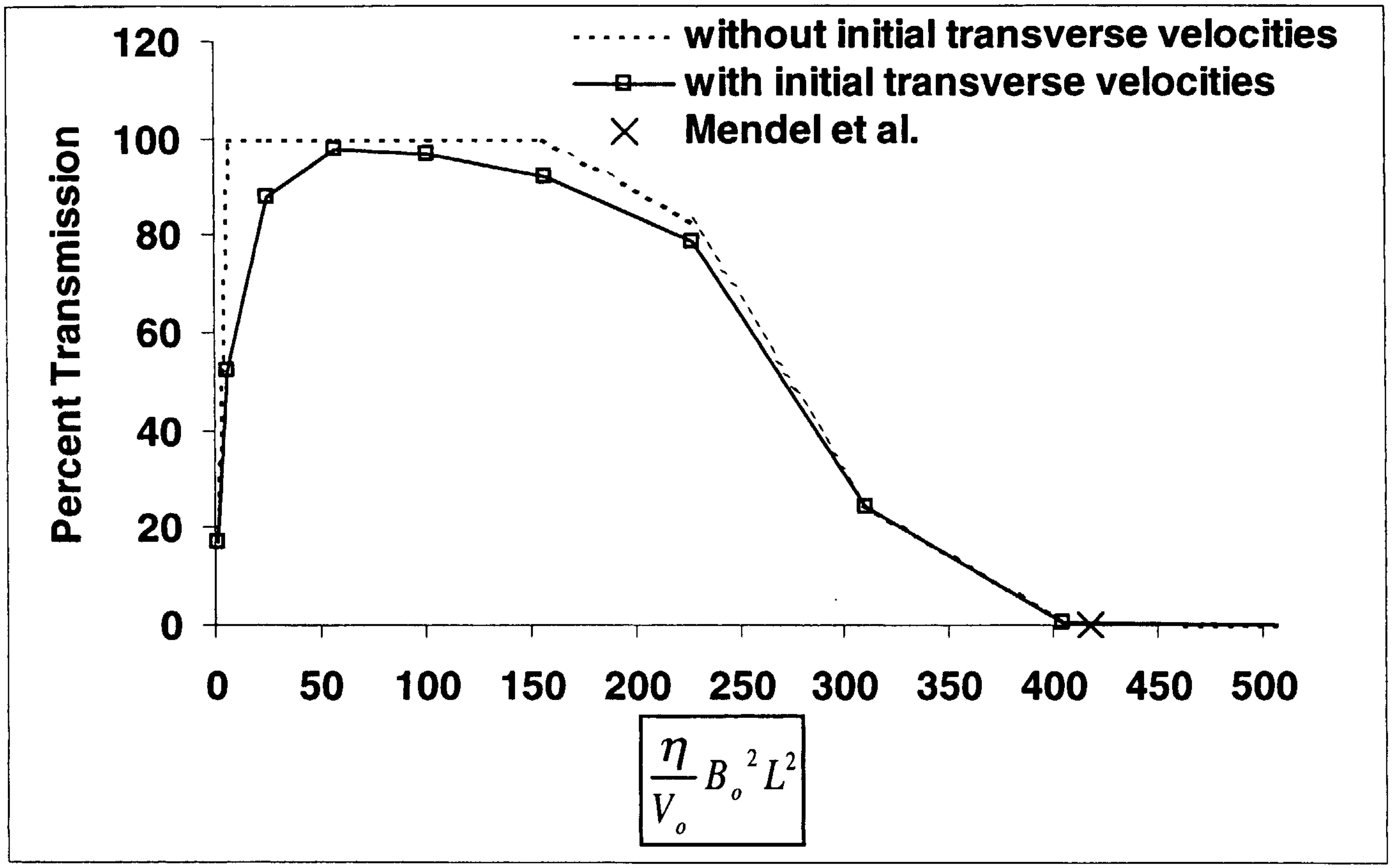
Percent Transmission



Percent transmission for 81mA beam for various values of flux density with and without initial transverse velocities

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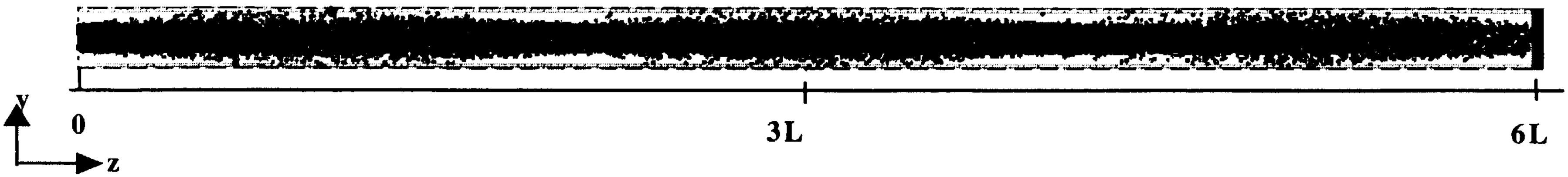
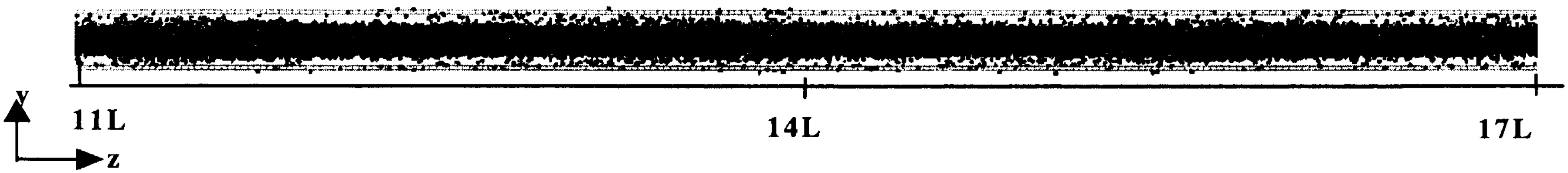
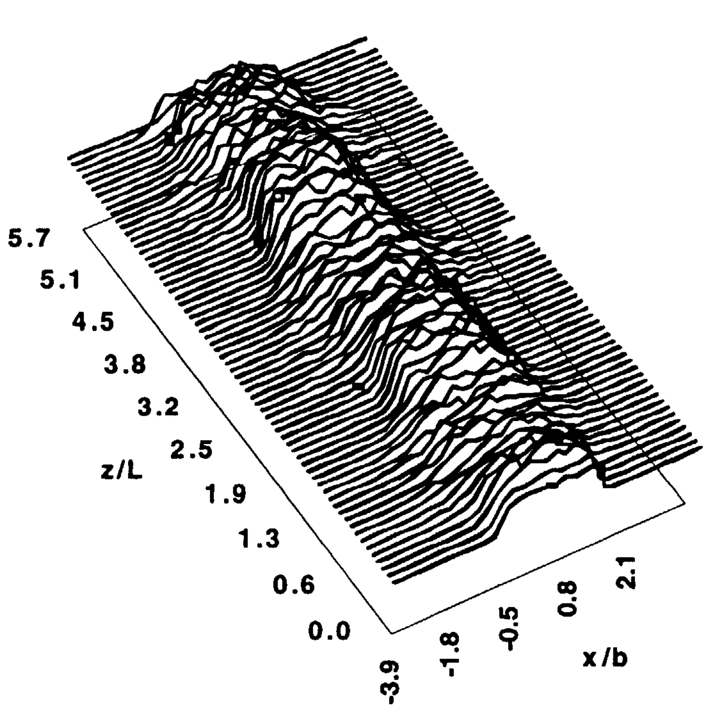
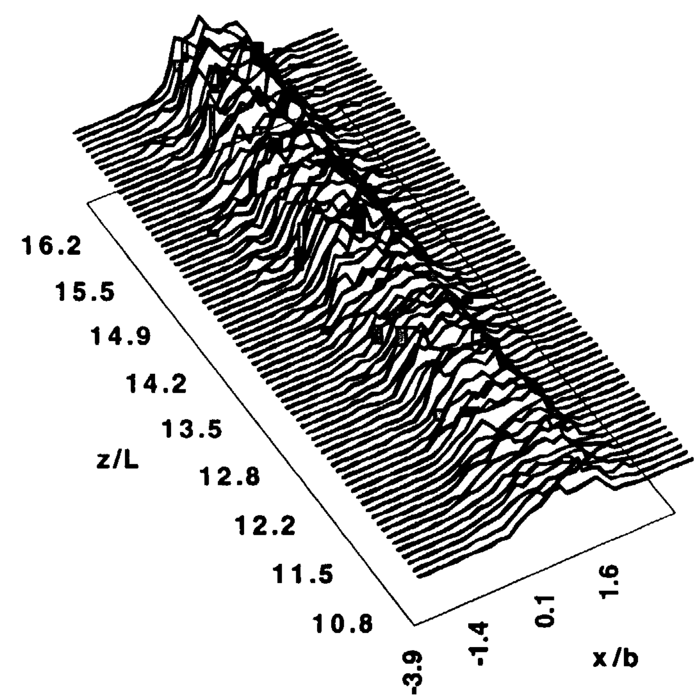
Tunnel Length- Beam profiles/current density 2*Brillouin with initial transverse velocities









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Summary

- Accurate 3D beam focusing model
- Excessive beam growth/RF circuit interception
  - backward wave oscillations, premature saturation, excessive circuit heating, decreased efficiency
- These imply serious reduction in tube performance
- 3D Model allows:
  - Asymmetric designs
  - Inclusion of Couplers
  - Input/Output sections
  - More accurate spent beam data for collector design