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.
ICOPS '99 IEEE International Conference on Plasma Science

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

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E11894
Tunnel length
Current density
Percent transmission
Percent ripple
Investigate
Thermal velocity model
Electron optics model - PIC solver
Periodic Permanent Magnet (PPM) stack - Static solver

MAFIA model
Hughes MPM TWL
Importance of Efficient Electron Beam Focusing

Summary
• More accurate spent beam data for collector design

• Input/Output sections

• Inclusion of Computers

• Asymmetric designs

3D Model allows:

These imply serious reduction in tube performance

• Decreased efficiency

• Excessive circuit heating

Electron beam/RF circuit interception causes:

• Premature saturation

• Backward wave oscillations

Excessive growth in beam diameter leads to:

Electron Beam Focusing
<table>
<thead>
<tr>
<th>V</th>
<th>a/b</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>Perveance (10-6)</td>
</tr>
<tr>
<td>0.12</td>
<td>I° (mA)</td>
</tr>
<tr>
<td>81.0</td>
<td>V° (kV)</td>
</tr>
<tr>
<td>7.6</td>
<td>Frequency (GHz)</td>
</tr>
</tbody>
</table>

Table: Operating Parameters for the Hughes 8916H Helical LWL
MARIA Code

Software
- Data Accepted Directly From Standard Engineering Design
- Simulation Code
- Three-Dimensional Electromagnetic Particle-in-Cell Algorithm
- Solution of Maxwell's Equations by the Finite-Integration

NASA
Permability used for magnets

Fixed magnetization and pole pieces

Provided B-H curve used for iron

- Calculate Magnetic Flux density, B
- Define material properties
- Static Solver

Mesh Generator

Model 3D PPM Stack

Cross-sectional view and top view of PPM Stack

\text{Sm2Co17 Magnet}

Iron Pole Piece

3D PPM Stack Model

Glenn Research Center

NASA
VERSUS Z/L

magnetic flux density $B_z$ on the PPM stack central axis
Simulated and analytical longitudinal component of

Longitudinal Magnetic Flux Density, $B_z$
Percent Ripple versus number of particles

\[ \frac{p}{\Delta} = \text{Ripple} \%

- Influence of self- and static fields
- Calculate particle motion under electron bunch
- Define emission properties of electron generator
- Define material properties
- Load B from PPM stack from static
- Particle-in-cell solver

Mesh Generator
- Model 3D beam tunnel
- Electron beam
- Magnetic focusing

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

3D Electron Optics Model

NASA Research Center
Thermal velocity model

Function

Distribution of ejection angle \( \theta \) according to mentioned Gaussian probability

Thus, particles trajectories are emitted across beam cross section with random

\[
\left( \frac{n}{n-1} \right)^{\frac{2}{n}} = \theta
\]

Ejection angle normal to the emission plane determined by

\( r^c = \) cathode disk radius

\( r^95 = \) beam radius containing 95% of beam current

\( T = \) cathode temperature in Kelvin

\( m = \) mass of electron

\( K = \) Boltzmann's constant

\[
\frac{m}{K T} \int_{r^c}^{r^{95}} \frac{1}{r} \, dr = \theta
\]

Standard deviation

Distribution based on Gaussian probability function with

Radial transverse velocities assumed

Clean Research Center

NASA
Parameter $\beta$ at Brillouin focusing

Percent ripple for various values of space charge

\[ \frac{3}{4d} = \frac{d\omega}{\omega} \]
\[ \left( \frac{\omega}{\frac{d\omega}{\omega}} \right) = \beta \]

Mendel et al.

Percent Ripple - Comparison to
Percent ripple for 8.1 mm beam with and without initial transverse velocities using various focusing strengths.
Percent Transmission for Glma beam for various values of

\[ \frac{V}{B} / \nu \]

Percent Transmission

Velocities

Flux density with and without initial transverse

Mendel et al.
Tunnel Length- Beam profiles/current density

2*Brillouin with initial transverse velocities
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