Modeling Neutral Beams in 3D MHD Equilibria

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ABSTRACT

Modern Tokamaks and stellarators have significant auxiliary fast ion heating systems which must be accounted for in equilibrium calculations. Direct measurement of fast ion profiles is difficult, so often in Tokamaks they are provided by forward modeling. The 3D nature of fields from Tokamaks with resonant magnetic perturbations (RMPs) and from stellarators necessitates a fully 3D model. The BEAMS3D code uses guiding center approximations to find particle trajectories from neutrals (or other fast ion sources) in 3D fields, and can include the physical effects of hot ion collisions and scattering, charge-exchange and recombination, pitch angle and energy scattering, and viscous velocity reduction. We benchmark the code for collisionless particle orbits in a circular cross-section, high aspect-ratio Tokamak, and we demonstrate beam injection and deposition. While currently designed to work with the equilibria produced by VMEC or with vacuum fields, the code easily could be modified to work with other equilibria.

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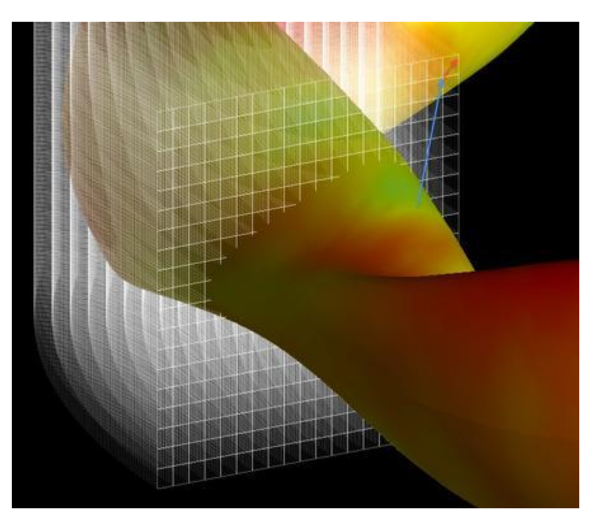
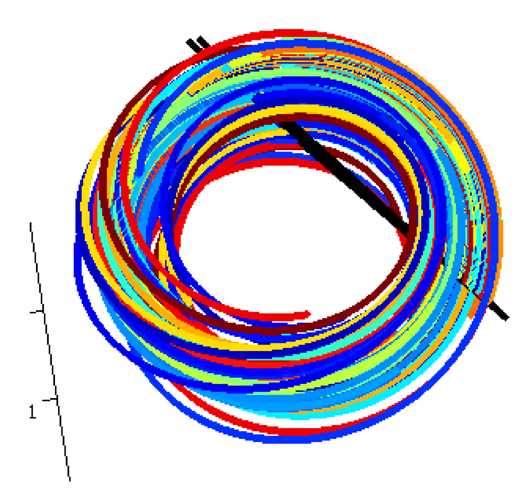
COMPUTATIONAL MODEL

VMEC equilibrium with a grid:



Beam deposition in DIIID:



- A general set of ODEs is solved for the guiding center motion of charged particles on a toroidal grid.
- The magnetic field from both vacuum and equilibrium calculations is constructed on a cylindrical (R, φ, Z) grid.
- ODEs are solved to arbitrary precision using standard numerical algorithms (NAG, LSODE).

$$\begin{cases} \dfrac{d\vec{R}}{dt} = \dfrac{\hat{b}}{qB} \times \left(\mu \nabla B + \dfrac{m v_\parallel^2}{B} (\hat{b} \cdot \nabla) \vec{B} \right) + v_\parallel \hat{b} \\ \dfrac{dv_\parallel}{dt} = -\dfrac{\mu}{m} \hat{b} \cdot (\nabla B) \end{cases}$$

$$\hat{b} = \frac{\vec{B}}{B}, \quad \mu = \frac{1}{2}\frac{m v_\perp^2}{B} = \text{constant}, \quad v_\parallel = \frac{d\vec{R}}{dt} \cdot \hat{b}(\vec{R})$$

- Particles can be deposited at arbitrary locations or by neutral beam deposition.
- Beam parameters include focal point, direction, aperture size, aperture distance, divergence, energy, and number of particles.
- Particles launched from focal point towards aperture plane assuming a Gaussian distribution in aperture plane (with given divergence).
- Ionization and charge exchange modeled using ADAS.

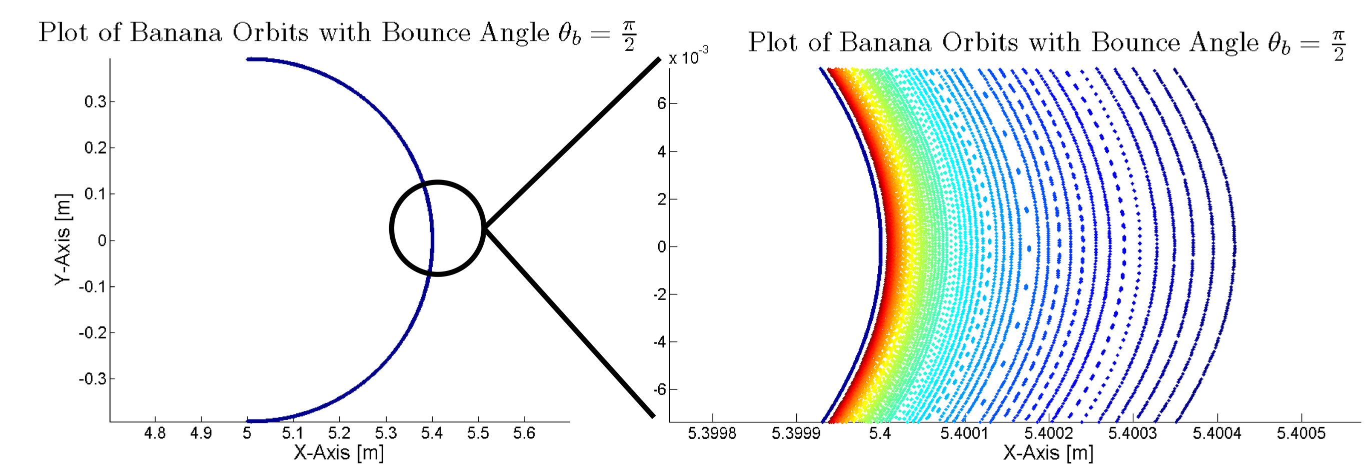
Beam deposition and charge-exchange model:

- Each particle is given a random number `randprob` in (0,1).
- A cumulative probability `cumprob` of having changed state (to/from ion/neutral) is recorded at each step.
- `cumprob` is found from the characteristic flight-time τ_{fl}. ADAS is called to gather cross-section data, which is used to find τ_{fl}.
- When `cumprob` falls below `randprob`, the particle switches state.

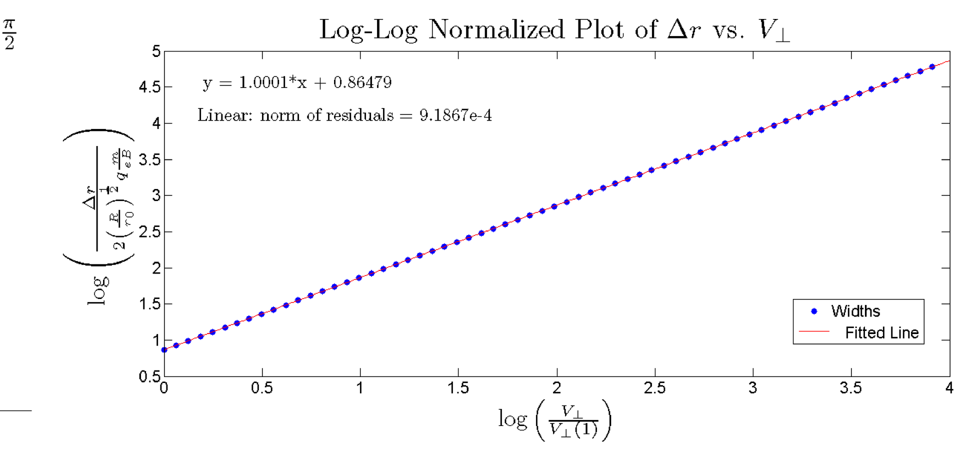
$$\tau_{fl} = \left[\sum_j n_j \langle \sigma_j v_{\text{rel}} \rangle \right]^{-1}$$

BENCHMARKING

Collisionless Particle Orbits:



Banana orbits for constant pitch, 2.5 order range in energy. A large aspect ratio (10) circular cross-section Tokamak field is used.

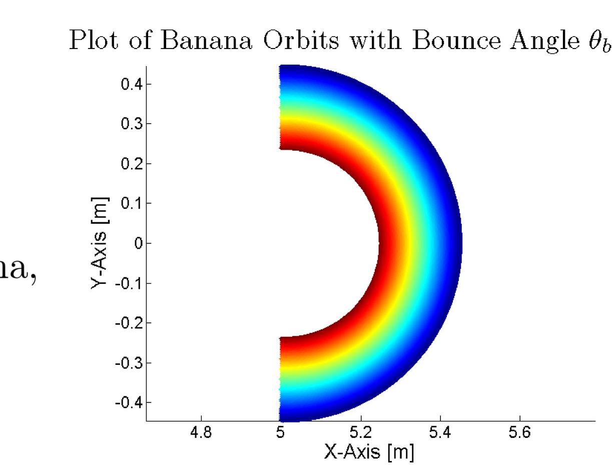


Normalized log-log plot of banana width vs. Vperp, showing a linear relationship, consistent with the analytic result for this B field.

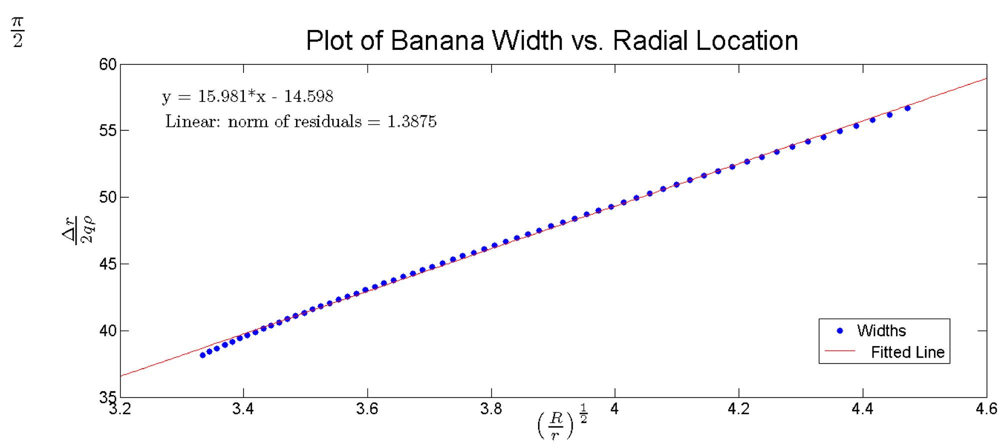
Banana orbits for constant pitch over a range of starting radial locations.

$$\Delta r = 2\left(\frac{R}{r}\right)^{1/2} q\rho$$

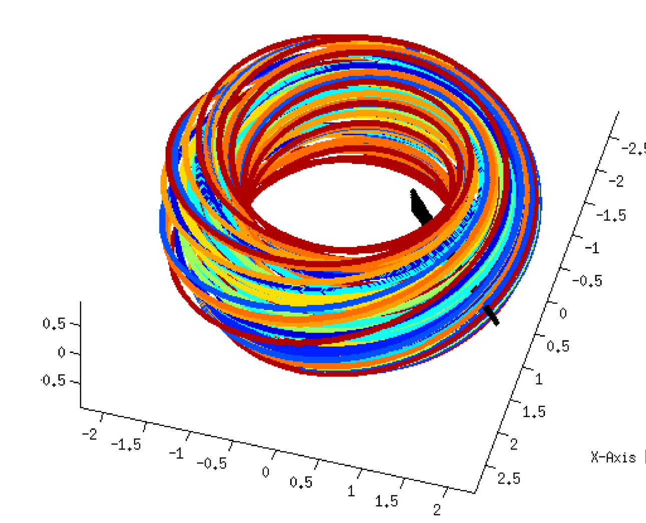
R is the major radius,
r is the radius from axis to banana,
q is the safety factor, and
ρ is the gyroradius.



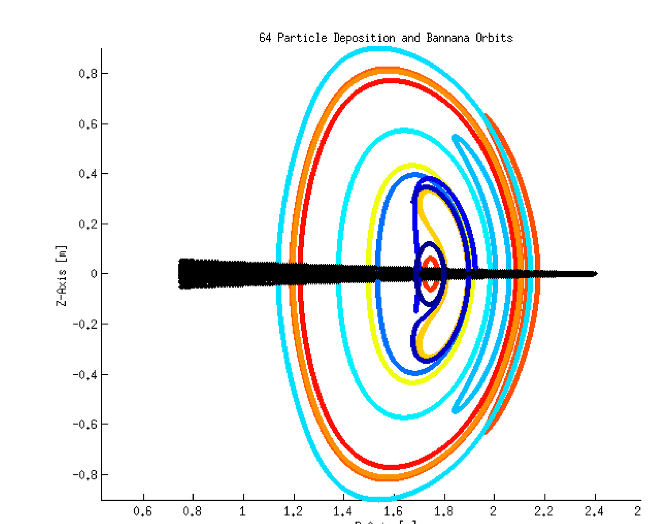
Normalized plot of banana width vs. radial starting location, consistent with the analytic result.



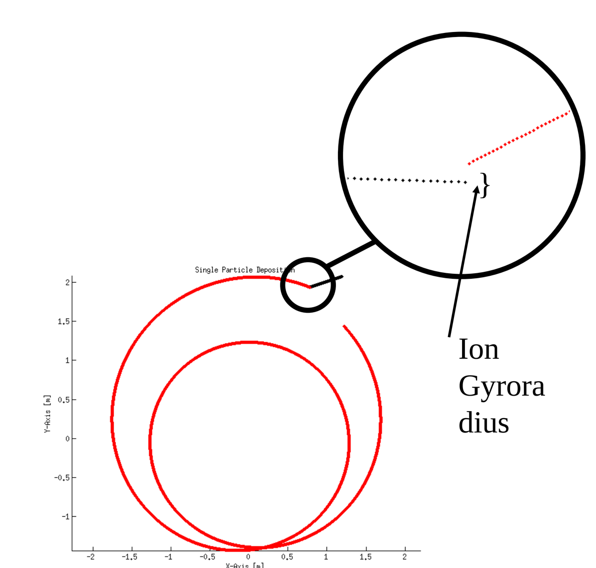
Neutral Beam Model:



Neutral beam (black) enters DIII-D with ionization from ion-impact and electron-impact governed by ADAS.



Flux space trajectories showing trapped and passing orbits in DIII-D

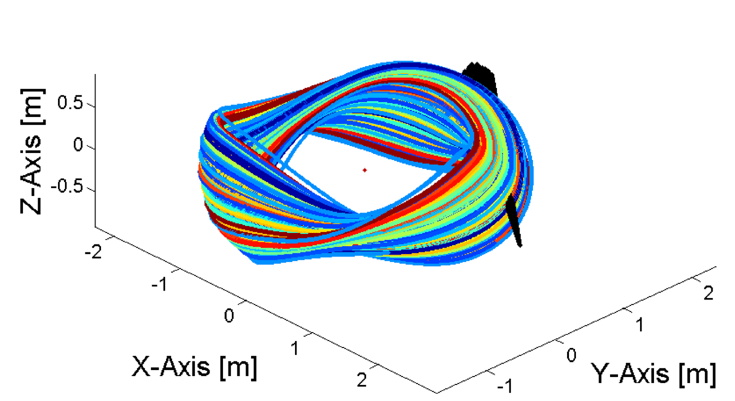


Ionization of a neutral particle showing the gyroradius step as it jumps to following the gyrocenter; the step is perpendicular to B.

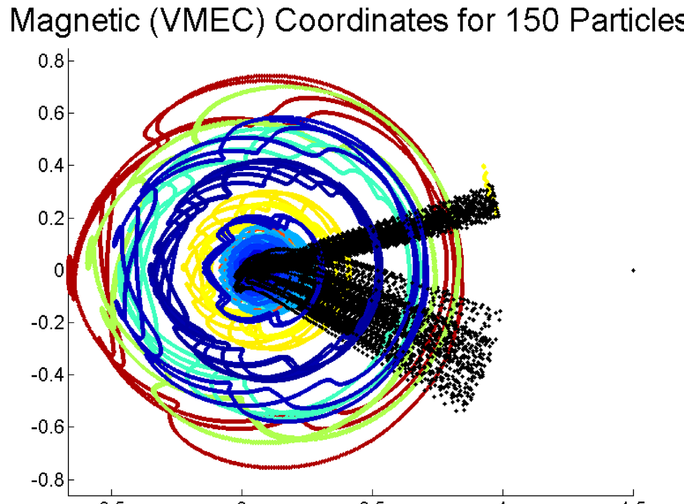
NCSX DEMONSTRATION

The fully 3D capability of BEAMS3D can be demonstrated using an NCSX VMEC equilibrium, with temperature and density profiles from Tokamaks with similar parameters.

3D NCSX Demonstration; Beam Deposition and Ion Orbits



Magnetic (VMEC) Coordinates for 150 Particles



DISCUSSION

- BEAMS3D is a fully 3D parallelized guiding center code for following particle trajectories and modeling neutral beam injection.
- BEAMS3D is interfaced with VMEC for MHD equilibria.
- Particles are tracked outside the last closed flux surface (LCFS) with vessel impact modeling.
- Monte Carlo beam model coupled with ADAS for atomic physics is currently under development, with much of the code structure completed.

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