Overview of the Distribution Function Component

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(but other team members have no responsibility for this draft)

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The distribution function, $f\left(t,\vec{r},\vec{v}\right)$, is the fundamental basis for describing a plasma

- f_s is a time-dependent function of the 6-D space that describes a particle and is the particle density in that 6-D space.
- The time evolution of f is given by $$\frac{df}{dt} = C\left(f \right) + sources + sinks$$ where $\frac{df}{dt}$ is the convective time derivative of a particle along its trajectory, e.g., $\frac{df}{dt} = \frac{\partial f}{\partial t} + \vec{v}\cdot\nabla f + \frac{q}{m}\left(\vec{E} + \vec{v}\times\vec{B}\right)\cdot\vec{\nabla}_v f$, and $C\left(f \right)$ is the Coulomb collision operator.
- In general, the electromagnetic fields must be determined self consistently from Maxwell's equations using the velocity moment f for each species as the current.
- Almost universally, we separate time scales, and evolve f_s with fixed E&M fields that are updated in time as required.

The distribution function component necessarily provides:

- The distribution function.

It may provide:

- Moments of the distribution function including current, particle fluxes, energy deposition, and stress and heat flux tensors.
- Transport coefficients that relate gradients to fluxes.
- Synthetic diagnostics such as neutron rates and neutral particle fluxes.

The distribution function component requires:

- Control variables, initial conditions.
- Geometry (limiters, wall location, etc.).
- Equilibrium fields $\vec{E}$ and $\vec{B}$ ($\vec{\nabla} B$).
- Temperatures and densities.
- Energy dependent sources and sinks.
- Data required for quasilinear diffusion tensor. This may be either the tensor itself, or the RF field data that allows its evaluation.

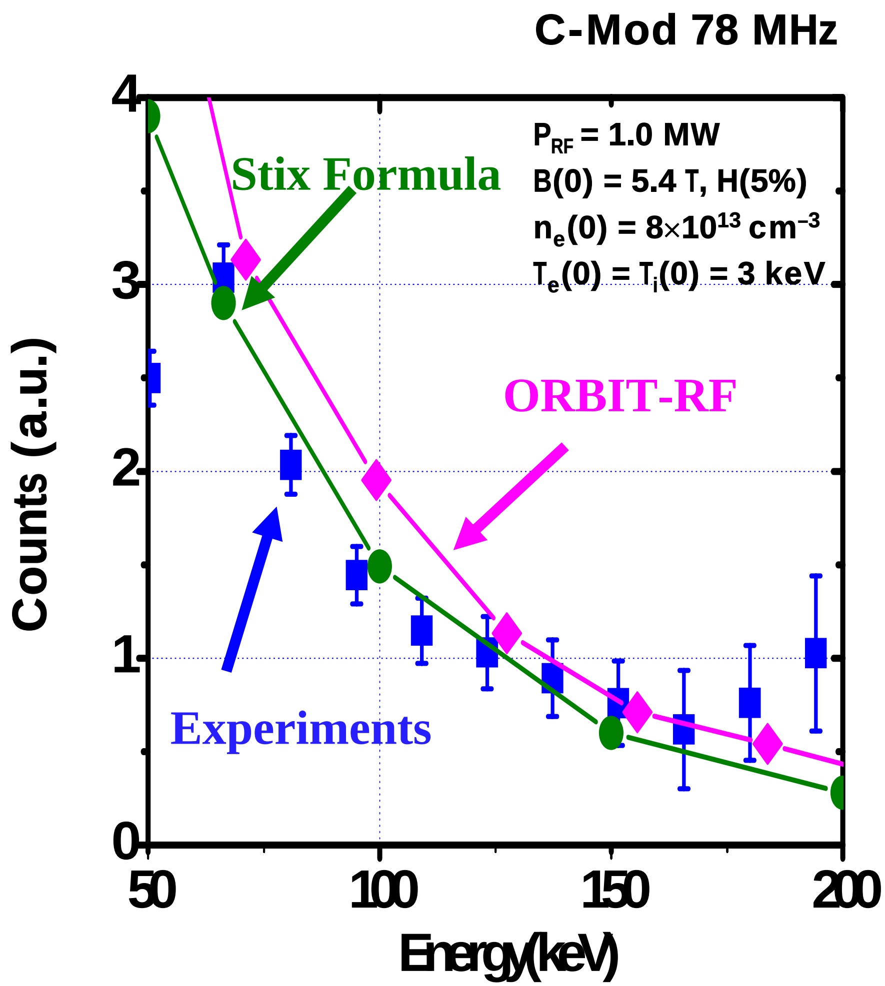
There are a wide range of distribution function codes with a range of capabilities and solution techniques

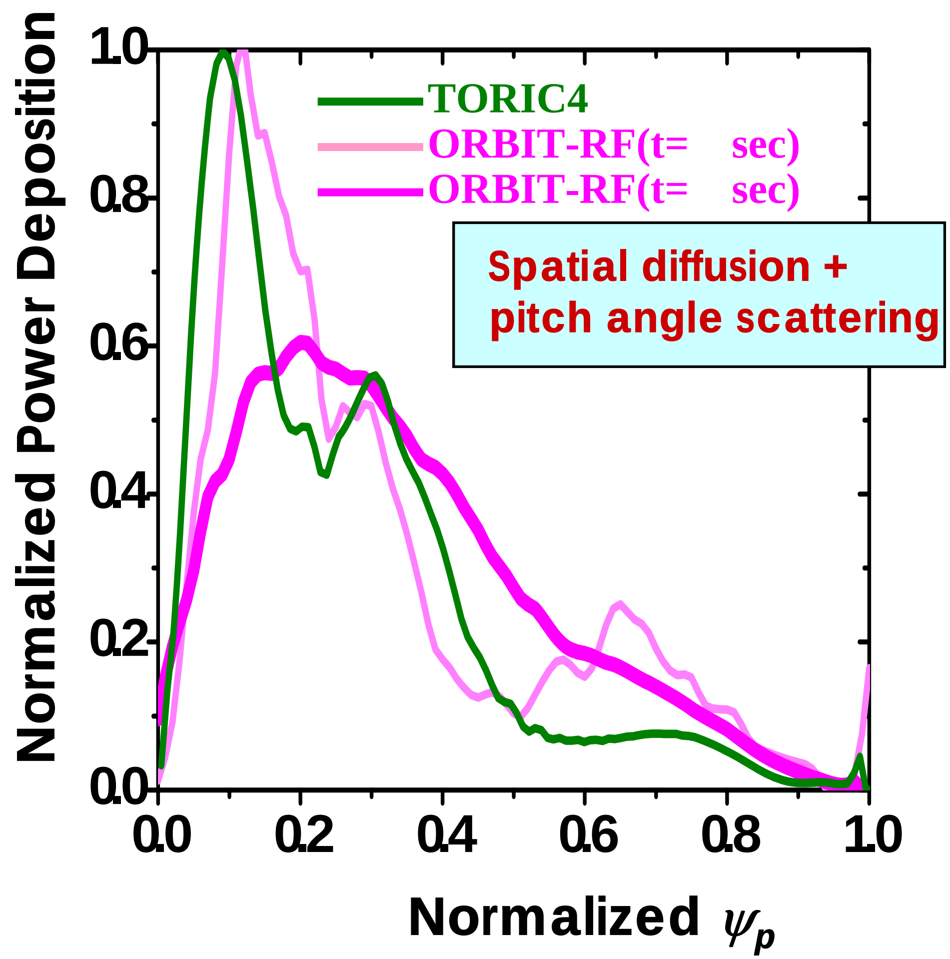
- ORBIT-RF
- DELTA5D
- DKES
- CQL3D
- Specialized (primarily for neutral beams)
  e. g. NUBEAM

ORBIT-RF
(M. Choi)

- Monte-Carlo particle code in 4-D. Particle guiding centers are followed using Hamilton's equations in toroidal and poloidal canonical momentum.
- Particles are not constrained to flux surfaces, and thus finite "banana" effects for energetic particles can be resolved.
- Particle diffusion is by collisions and quasilinear diffusion from a specified wave spectrum in $k_\perp$, $k_\parallel$.
- Applications include fundamental heating at the ion cyclotron frequency and high harmonic interactions with fast ions from neutral beam injection.

ORBIT-RF Agrees with Measured Minority Ion Spectrum From NPA For C-Mod Minority Heating Scenario





DELTA5D
(Don Spong)

- **Delta-f Monte-Carlo particle code in 5-D. Guiding centers are used for particle advancement.**
- **Full 3-D particle orbit effects resolved.**
- **Particle diffusion is by collisions, QL RF.**
- **New delta-f holds MHD variables constant.**
- **Applications include stellarator transport and stellarator energetic particle dynamics.**

Drift Kinetic Equation Solver (DKES)
(S. Hirshman)

- Solves for perturbed distribution function with 2-D space, 1-D velocity (pitch angle) resolution on each flux surface. Provides steady-state, surface-averaged transport coefficients of heat, particles, and current using a variational principle. Diffusion is driven by Coulomb collisions, and drift orbits are assumed to have small departures from flux surfaces.

- Primary use has been for tokamak/stellarator transport coefficients.

- Can be used to examine local fluxes within a surface.

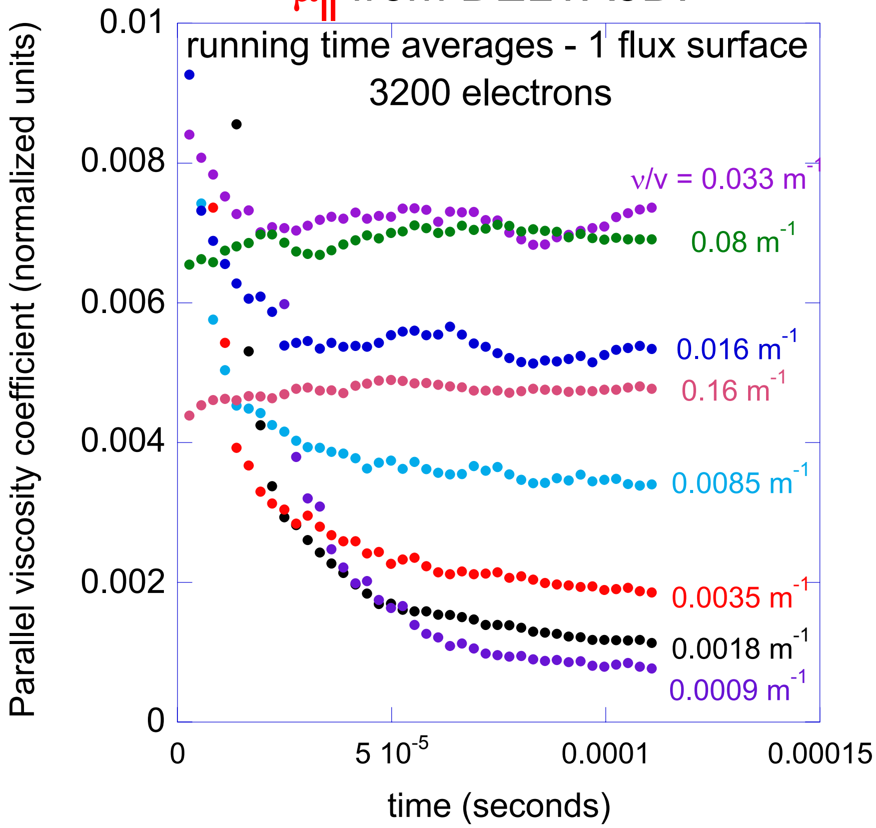
New MHD viscosity-based closure relations are more consistent with the MHD model

DELTA5D

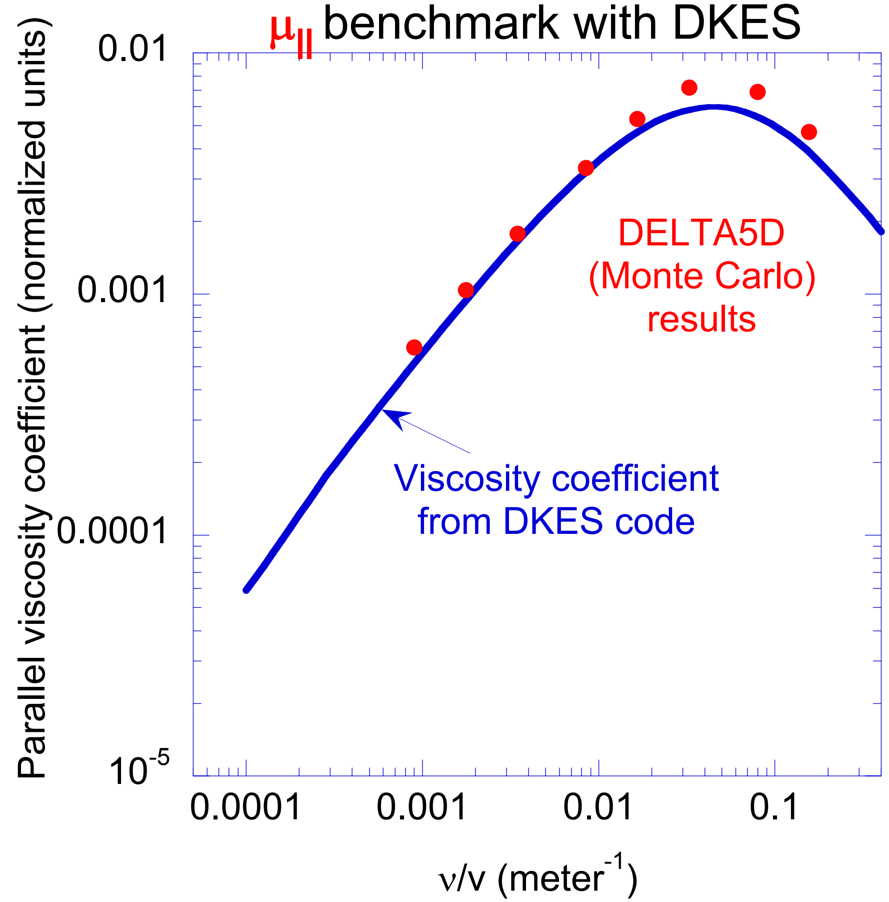
$$\begin{bmatrix} \mathbf{B}\cdot(\nabla\cdot\Pi) \\ \mathbf{B}\cdot(\nabla\cdot\Theta)\end{bmatrix} = \begin{bmatrix} M_1 & M_2 \\ M_2 & M_3\end{bmatrix}\begin{bmatrix}V_\parallel \\ Q_\parallel\end{bmatrix} + \begin{bmatrix}N_1 & N_2\\ N_2 & N_3\end{bmatrix}\begin{bmatrix}\frac{1}{n}\frac{\partial p}{\partial s} - e\frac{\partial\phi}{\partial s} \\ -\frac{\partial T}{\partial s}\end{bmatrix}$$

where $M_j, N_j \propto \int_0^\infty dE\, e^{-E/kT}\sqrt{E}\left(E-\frac{5}{2}kT\right)^{j-1}$ $\mu_\parallel, N(E)$

$\mu_\parallel$ from DELTA5D:



$\mu_\parallel$ benchmark with DKES

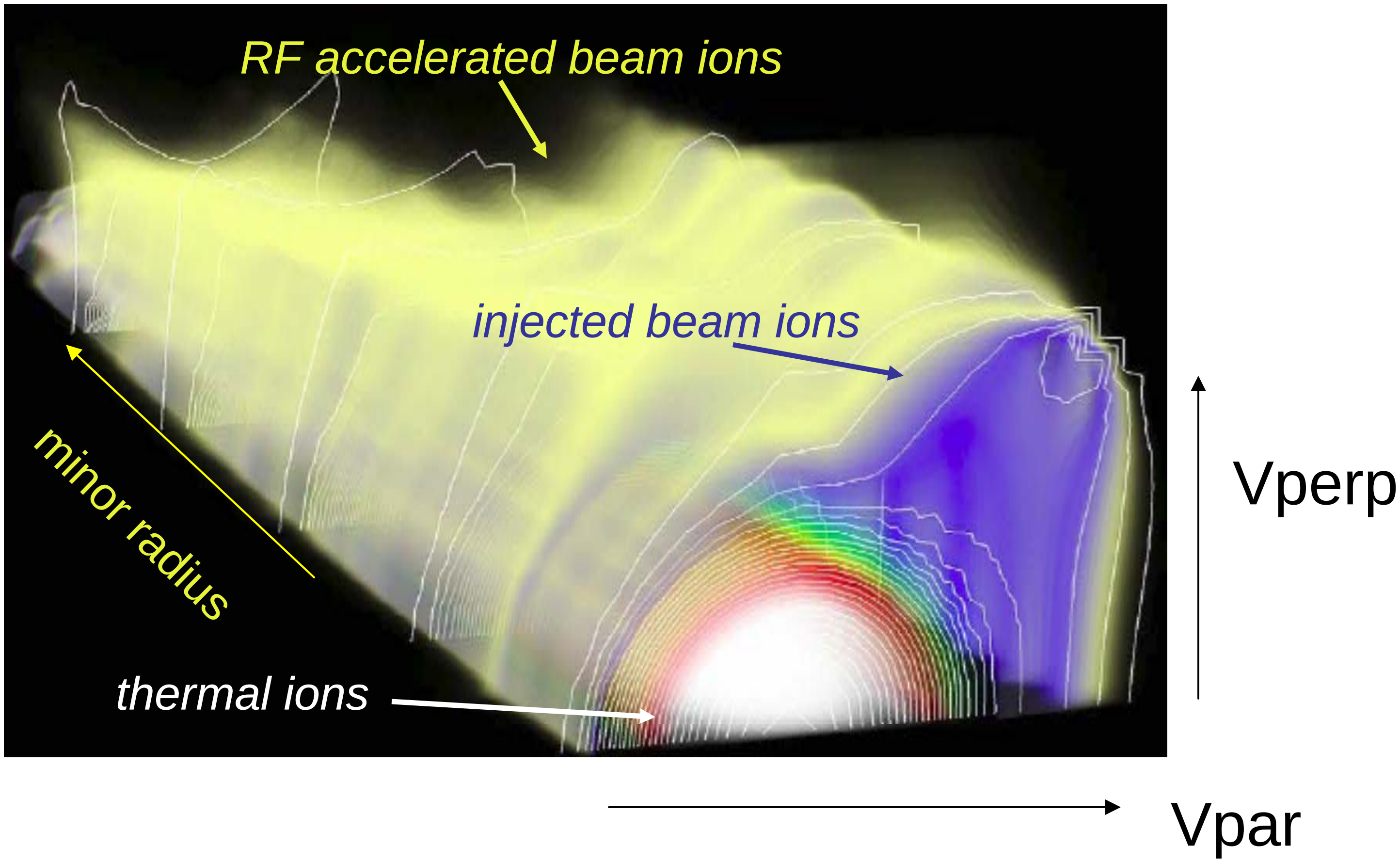


* DKES: Drift Kinetic Equation Solver

CQL3D
(Bob Harvey)

- Solves bounce averaged Fokker-Planck equation in 3-D (2-D velocity, 1-D space).
- Velocity diffusion is driven by Coulomb collisions and RF quasilinear diffusion.
- Spatial diffusion is via a (specified, but velocity dependent) radial diffusion constant.
- Has been used for a wide range of RF problems—LH, ICH, HHFW, ECH, EBW, etc.

As part of the RF SciDAC project, CQL3D and AORSA2D have been solved self consistently



Simulation of deuterium distribution function in DIII-D resulting from combined RF heating and neutral beam injection

Jaeger et al APS 2005

There are many opportunities for code enhancements.

As examples:

- **DELTA5D—include RF-driven diffusion via diffusion tensor instead of individual modes.**

- **ORBIT-RF—use drift-orbit averaged QL operator to eliminate need for 4-D data file.**

- **DKES—change to 1-Dspace, 2-D velocity to follow energy as well as pitch angle diffusion for RF.**

- **CQL3D—include drift orbit effects in RF diffusion via drift orbit averaged QL operator; include finite banana transport via velocity dependent special diffusion.**

Some comments

- Particle-based algorithms naturally include detailed orbit effects, but may require a large number of particles to give RF codes a smooth distribution function. Particle to function transformations are likely needed.

- Particles are most efficiently followed in constants of motion space: RF codes require configuration space data. Efficient and accurate techniques this transformation may be required.

- The need for holding MHD independent variables (pressure, density, magnetic field, current) constant needs to be evaluated. Is it necessary for fast campaign?