The STELLA 3D Fokker-Planck Code

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History:

- Originally, calculation of f(v,θ,s_along_**B**;t) with $v_{||}$.df/ds-term (i.e. NOT bounce-averaged) used for neoclassical resistivity at all collisionalities (Sauter, Harvey, Hinton, Contr Pl Phys (1994)), subsequently Sauter-bootstrap-current formulas (Sauter, Angioni, Lin-Liu, PoP (1999)). Part of CQL3D
- Then with $E_{||}$, applied to tokamak divertors (Kupfer, Harvey, Phys Pl (1996)), called FPET
- Adjusted for multi-species application to solar wind (~2000), with Smirnov, renamed STELLA
- Recently B field variation added.

Divertor Application: Why Kinetic Modeling of SOL?

- Heat flux carried by electrons at $v \sim 3V_{Te}$ [Remember: $V_{coll} \propto 1/v^3$]

$$\Rightarrow \quad \frac{\lambda_{mfp}\big|_{3V_{Te}}}{L_{along\ B}} > 1 \text{ , typically}$$

$\Rightarrow$ Kinetic effects important (often) for heat transport in SOL
(Ad Hoc flux-limiting factor is often used in the fluid treatment)

- Localized cooling (e.g. Marf's) increases “temperature” gradient
  $\Rightarrow$ Kinetic effects.

FPET/Stella

Solves Fokker-Planck Eqn for distr. function $f\,(v$ [speed], θ [pitch-angle]), for e, i at each s [distance] along **B:**

$$\frac{\partial f(v,\theta,s,t)}{\partial t} + v_{\|}\frac{\partial f}{\partial s} + \frac{qE_{\|}}{m}\frac{\partial f}{\partial v_{\|}} = C(f) + D_{RF}(v,\theta,s) + S(v,\theta,s)$$

$C(f)$ = Non-Linear RMJ Coulomb Collision Operator

$D_{RF}(v,\theta,s)$, $S(v,\theta,s)$ are 3D RF diffusion terms and particle sources, with B.C.'s and $E_{\|}$ for given flux(s), chosen to maintain charge neutrality.

Solution of finite difference eqns is by Alternating Direction Implicit:
1) Implicit vel. step based on CQL3D algorithm, with explicit s-dependence
2) Implicit (tri-diagonal) solve in s, with explicit vel-dependence

$E_{\|}$ is determined by an iterative procedure so that e,i-fluxes are equal.
(Kupfer, Harvey, Phys. of Plasmas 3, 3644 (1996))

Boundary Conditions in FPET/Stella

Four Categories:

1) General Divertor

$f_{in} = F_1(f_{out}) + \alpha_1 f_{m1}$

$f_{in} = F_2(f_{out}) + \alpha_2 f_{m2}$

Presently:

Ions: $F_2 = 0$

Electrons: $F_2 = f_{out}$, $v_{||} < v_{max}$

0 otherwise

2) Divertor 1

$f_{in} = F(f_{out}) + \alpha f_{m2}$

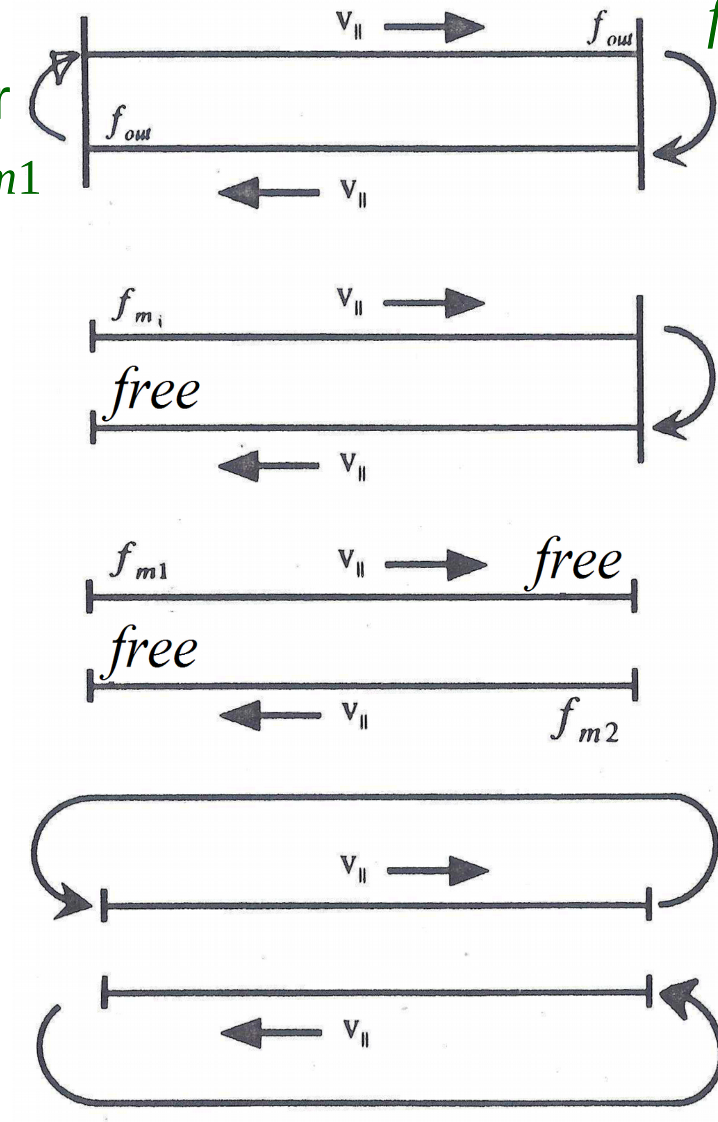
Ions: $F = 0$

Electrons: $F = f_{out}$, $v_{||} < v_{max}$

0 otherwise

3) Divertor 0

4) Periodic



Sequence of Calculations for Combined Electron-Ion Problem

(General Divertor Case)

0. Initialize with Maxwellian electron and ion profiles, plus sources.

1. Time step electrons to ~steady-state, with $E_{||k}$ chosen for constant $n_e(s)$.

2. Single time step ions with E_k determined (in 1.) from electrons.
   Ion Δt is much greater than electron Δt.
   This will permit ion density profile to relax.

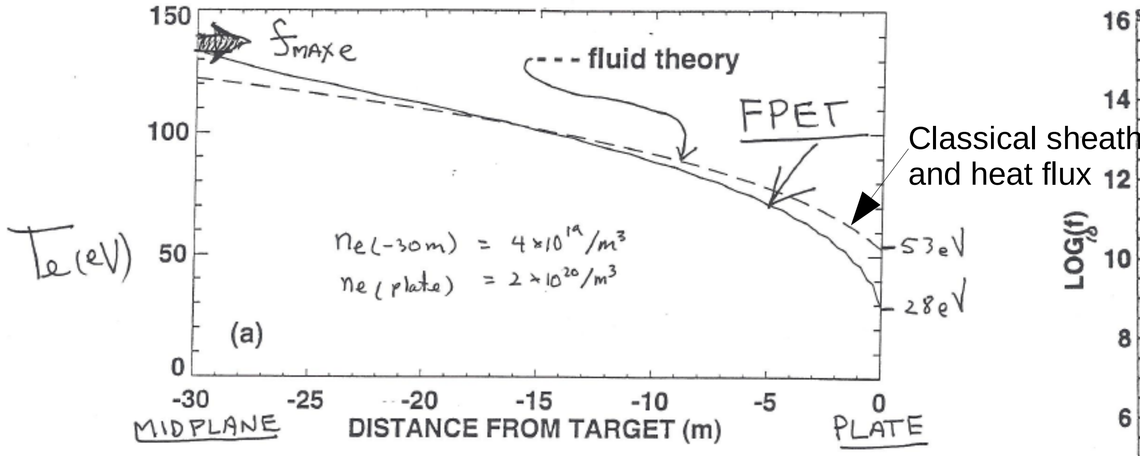
3. Several electron time steps, to get quasi-state $E_{||}$

- Time-step to steady-state

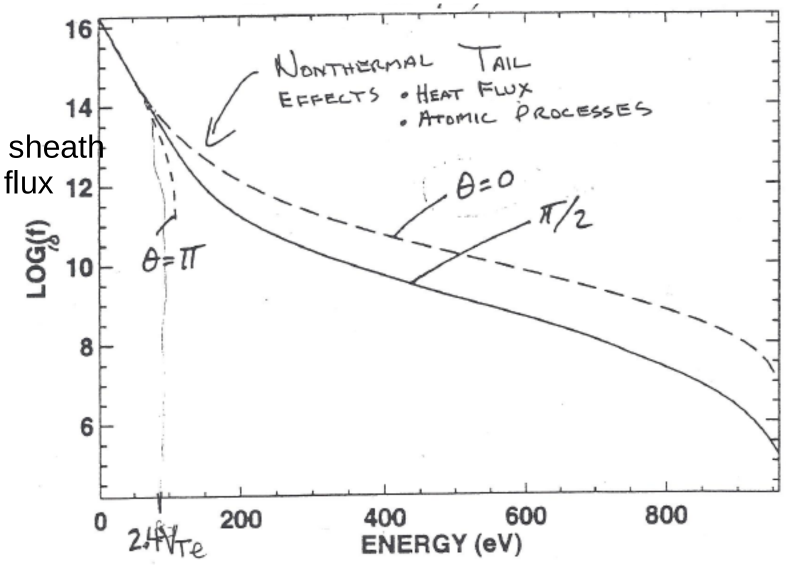
- Basically, electrons determine $E_{||}$ and ions accelerate to C_s due to $E_{||}$

Comparison of Fluid and Kinetic Solutions in a Tokamak Divertor

Deviation from Fluid Theory

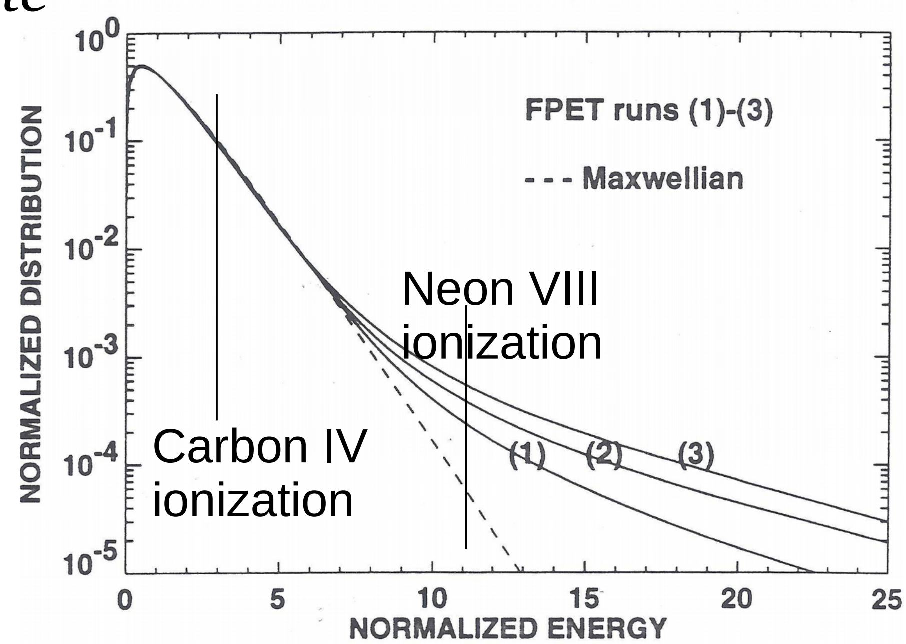


Electron Distn Function Near Plate



Ion Distn is ~Shifted Maxwl at vel c_s
+ similar tail toward the divertor plate.

$\langle f_e \rangle_\theta$ *near plate*



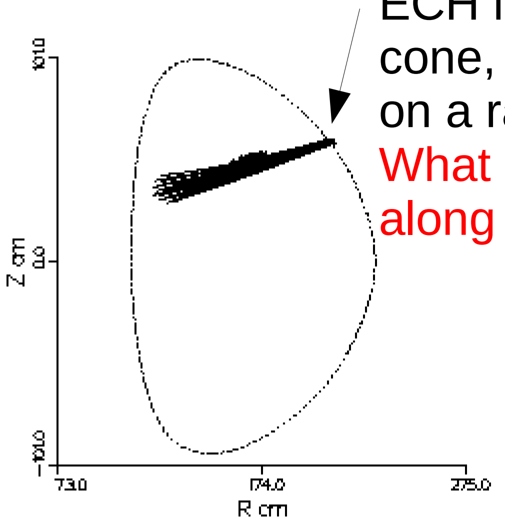
n_{e0} = 4·10^{13} /cm^3 , $n_{e,plate}$ = 2·10^{14} /cm^3

$T_{e,plate}|_{initial}$ = 14 eV (Run 1), 30 eV (Run 2), 53 eV (Run 3)
T_{e0} = 74 eV (Run 1), 108 eV (Run 2), 140 eV (Run 3)

$$\tilde{E} = \frac{\frac{1}{2} m_e v^2}{T_{local}}$$

Effects of nonthermal tail: Revised Bohm sheath condition
Modified heat conductivity
Strong modification of ionization rates
Etc

Another Application
ECCD by Power Deposited in Localized EC Spot On A Field Line



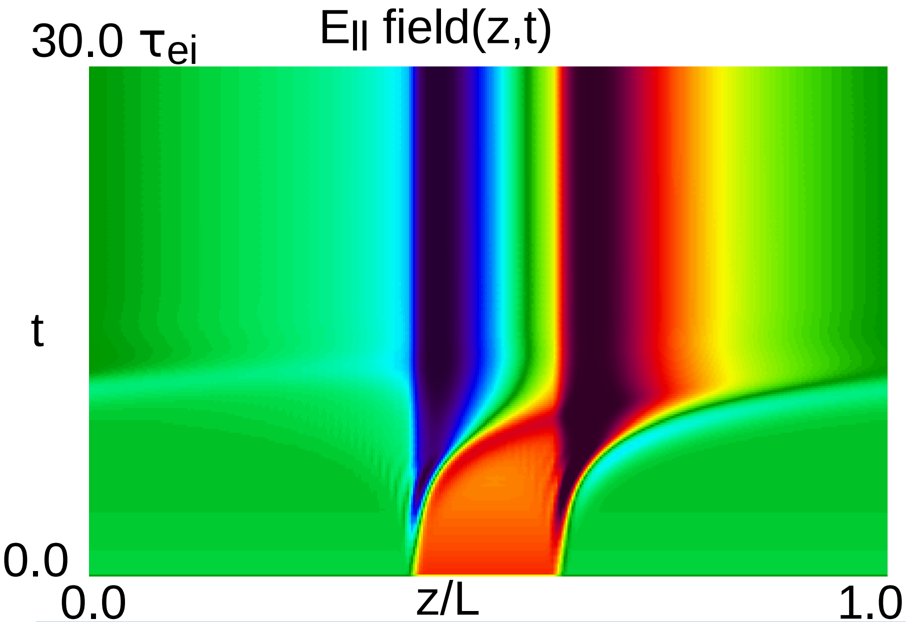
ECH injected in narrow cone, heats localized spot on a range of flux surfaces.
What keeps electron current going along **B**, outside of the spot?

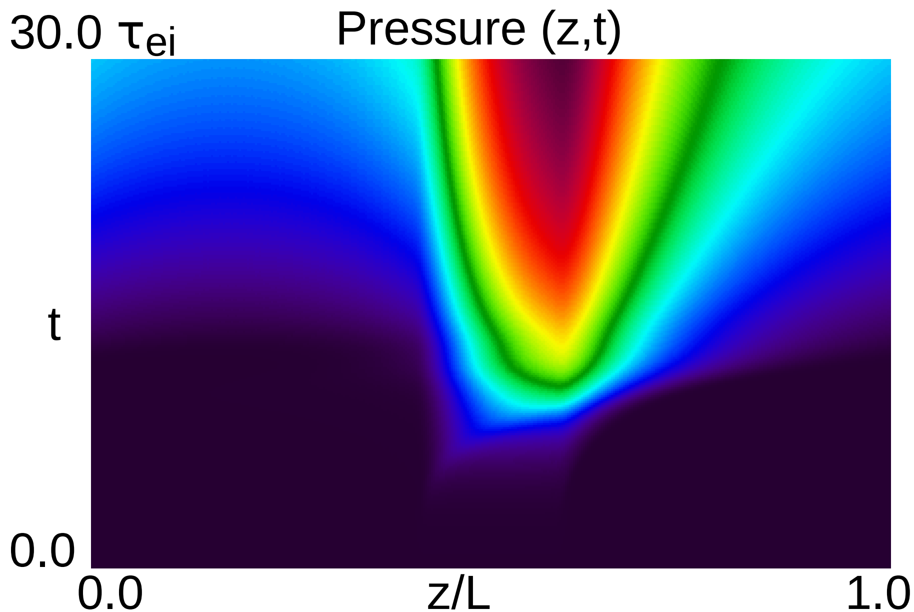
The connection length around the tokamak until the B-field connects back to the spot (2/3 overlap) is about 20 toroidal rotations.

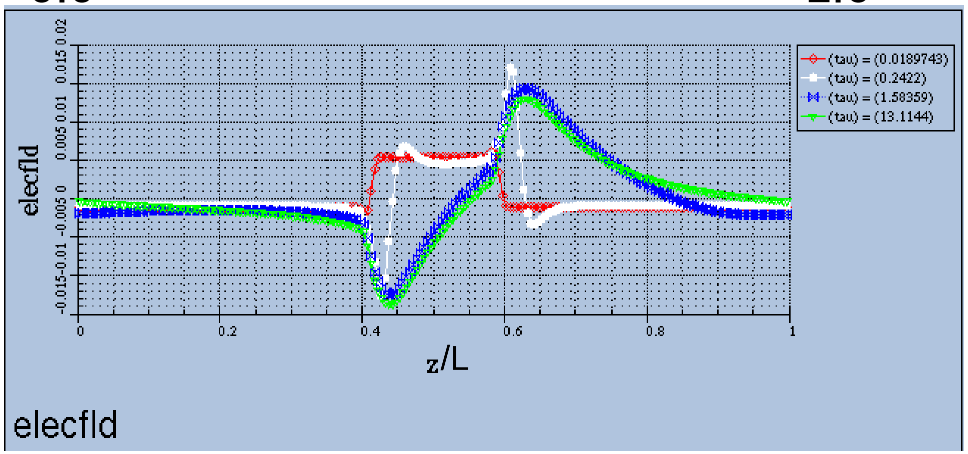
$L_{connection} \sim \lambda_{mfp}$

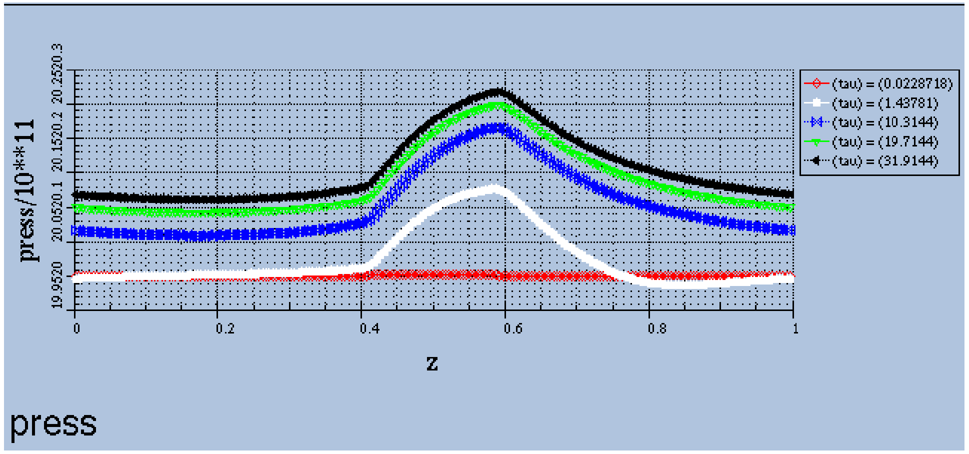
Model $f_e(v,\theta,z;t)$ roughly in STELLA with periodic BCs and RF parallel (or perp) diffusion localized over 0.2 of total length of a field line, L~100 m, under typical tokamak plasma conditions.

Parallel Electric Field and Pressure Build up Over Period $\gtrsim 10\ \tau_{ei}$



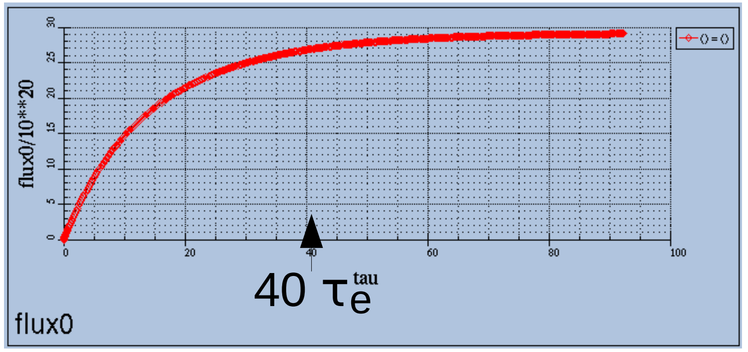






Observations from Model for Localized ECH on Tokamak Flux Surface

- Electrons are on avg accelerated in the RF region, and collisionally slow down over the rest of the connection length, creating bunching (space charge) and $E_{||}$.
- Pressure buildup is also an important part of the dynamics.
- Thus, a force, $F_e = -eE_{\|} - \frac{1}{n_e}\frac{\partial p_e}{\partial z}$, in addition to momentum input from the RF. This force maintains continuity of the current within the toroidal circuit:
  - F_e: Retards the e-current in the RF region, accelerates it outside.
  - Net work around the circuit by Fe is zero: $\oint F_e ds = 0$
    So, no net effect of these additional forces, relative to usual uniform plasma calcs of current drive efficiency.
- CD efficiency agrees with uniform plasma theory
- (Harvey et al., Proc. of RF Power in Plasmas Mtg, Annapolis (1999))
- The current turns on rather slowly:



- This model illustrates STELLA capabilities for calculation of the ambipolar electric field over a range of collisionality regimes, from collisionless to collisional.

Possible Relation of This Work to FRC

CQL3D Bounce Average Approach:

- May be adapted for electron tail heating by ECH or HHFW
- Trapped particles in field reversed region, transiting outside
- Ions, could get some rough estimates, but gyro-orbits are large

STELLA non-bounce-averaged approach:

- Seems can be quite accurate for parallel electron transport, and has no limitations regards multiple minima of |**B**|
- Could work well for calculation of ambipolar electric fields, including the exhaust region. Would run the code on a radial array of flux surfaces.
- Sources and sink readily added for ionization and recombination
- RF diffusion heating can be added, coupling to GENRAY
- Ion modeling would not be very accurate, due to large gyro-orbits