Tempest 4D Edge Gyrokinetic Simulations

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48th APS DPP conference, Nov. 2nd, 2006, Philadelphia

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Equations

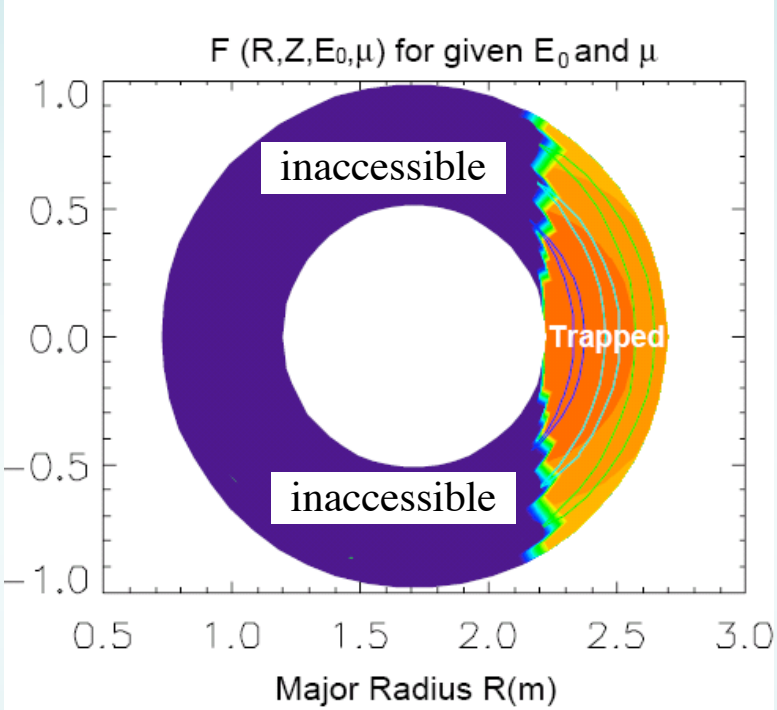
- Ion gyro-kinetic equations in (ψ, θ, ζ, E, μ) coordinates.

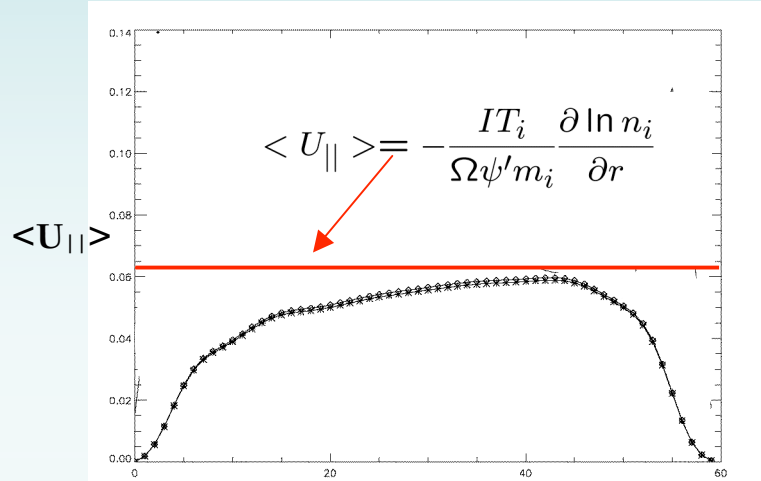
$$
\begin{aligned}
\frac{\partial F_\alpha}{\partial t} &+ \bar{\mathbf{v}}_{\mathbf{d}} \cdot \nabla_\perp F_\alpha + (\bar{v}_{\|\alpha} + v_{Banos}) \nabla_\| \partial F_\alpha \\
&+ \left[q \frac{\partial \langle \Phi_0 \rangle}{\partial t} + \bar{\mu} \frac{\partial B}{\partial t} - \frac{qB}{B^*} \bar{v}_\| \nabla_\| \langle \delta\phi \rangle - q \mathbf{v}_{\mathbf{d}}^0 \cdot \bar{\nabla} \langle \delta\phi \rangle \right] \frac{\partial F_\alpha}{\partial E_0} \\
&= C(F_\alpha, F_\alpha),
\end{aligned}
$$

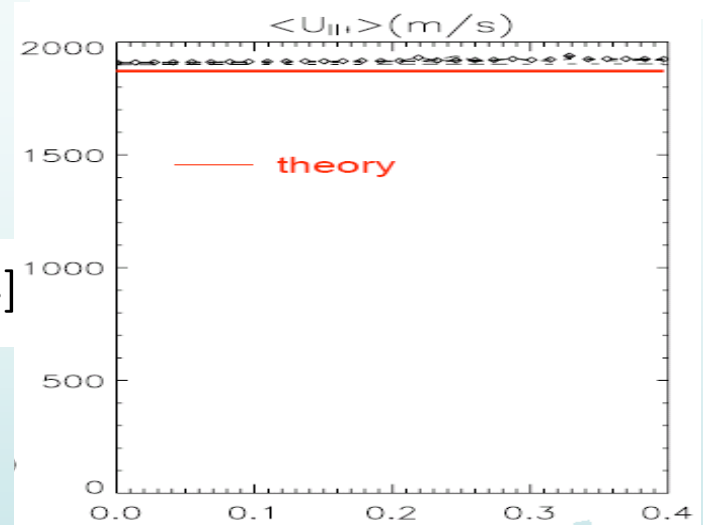
- Gyro-kinetic Poisson equation (long wave length limit).

$$
\begin{aligned}
\left(\sum_\alpha \frac{\rho_\alpha^2}{2\lambda_{D\alpha}^2} \right) \nabla_\perp^2 \Phi &+ \left(\sum_\alpha \frac{\rho_\alpha^2}{2\lambda_{D\alpha}^2} \nabla_\perp \ln N_\alpha \right) \cdot \nabla_\perp \Phi + \nabla^2 \Phi \\
&= -4\pi e \left[\sum_\alpha Z_\alpha N_\alpha(\mathbf{x}, t) - n_e(\mathbf{x}, t) \right] - \sum_\alpha \frac{\rho_\alpha^2}{2\lambda_{D\alpha}^2} \frac{1}{N_\alpha Z_\alpha e} \nabla_\perp^2 p_{\perp\alpha}.
\end{aligned}
$$

Tempest reproduces neoclassica parallel flow in ring geometry





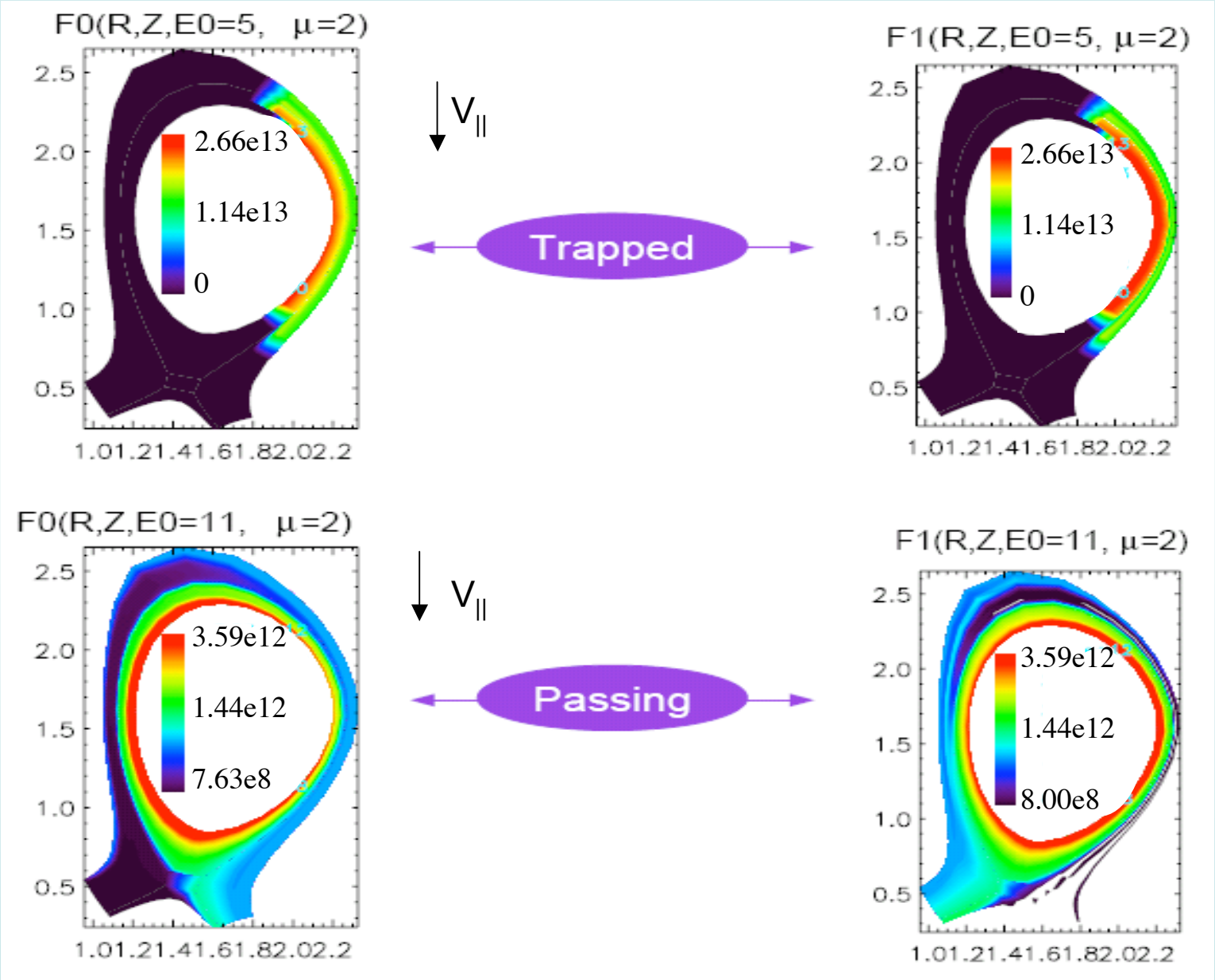


$$< U_{||} >= \frac{IT_i}{\Omega\psi' m_i}[(k-1)\frac{\partial \ln T_i}{\partial r} - \frac{\partial \ln n_i}{\partial r} + \frac{e}{T}E_r]$$

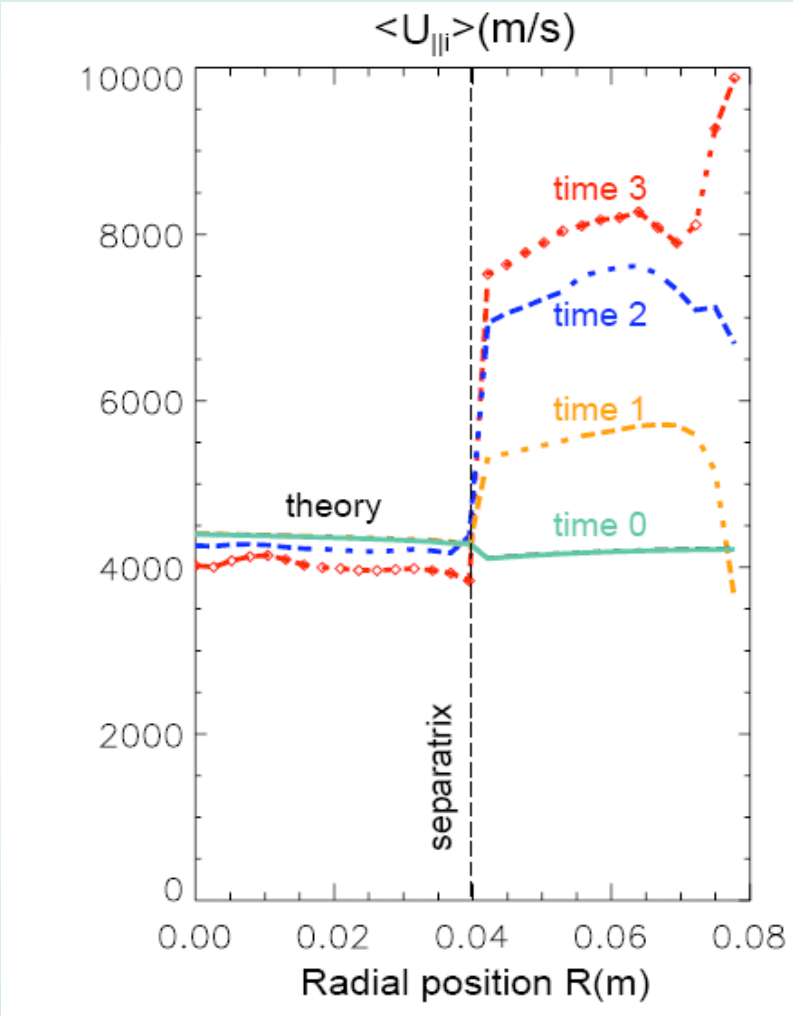
Simplest case: circular geometry

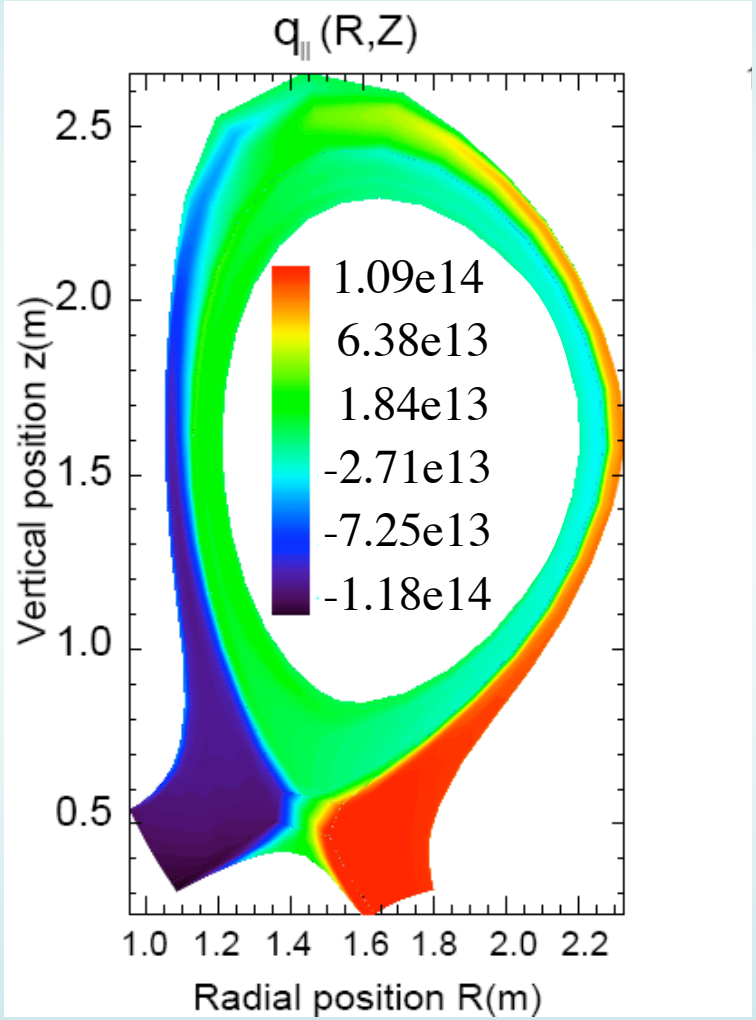
$$\frac{\partial T_i}{\partial r} = E_r = 0$$

Distrib. Funct. in a divertor geometry



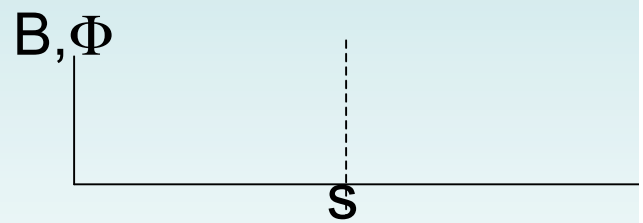
TEMPEST recovers theoretical $U_{||}$ inside separatrix and increase as expected in SOL

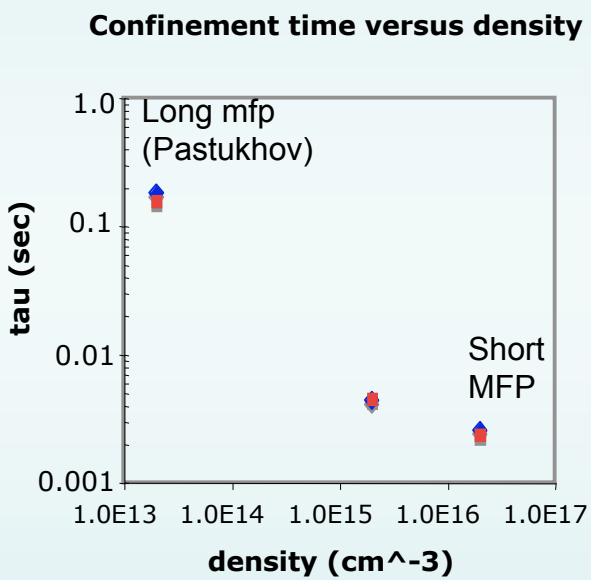


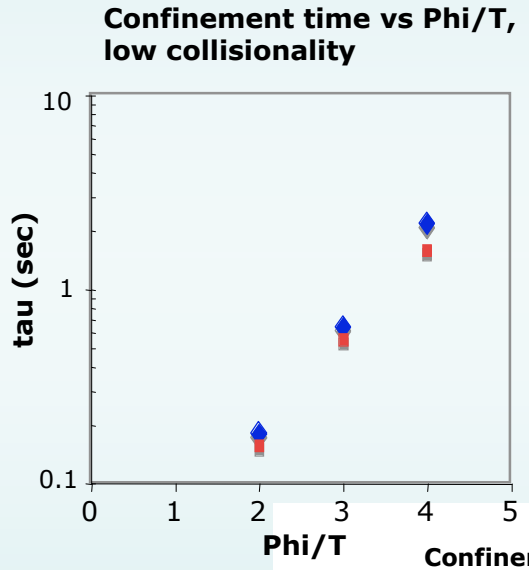


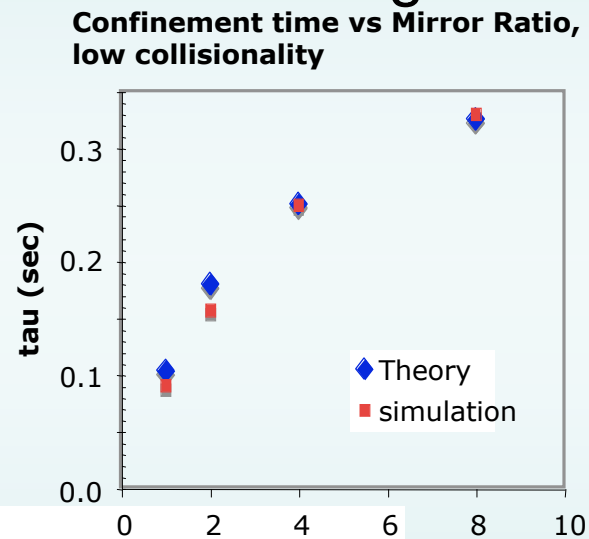
Endloss tests (1-D, 2-v) demonstrate viability of continuum code with real collision operator (CQL

- Collisional endloss ("Pastukhov") test cases
  - Uniform B and Φ with confining mirror ratio and potential jump at wall. (3D: 1-x, 2-v)

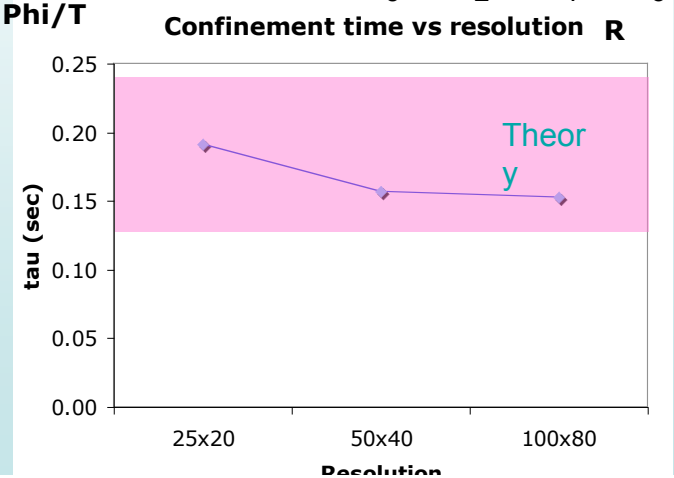






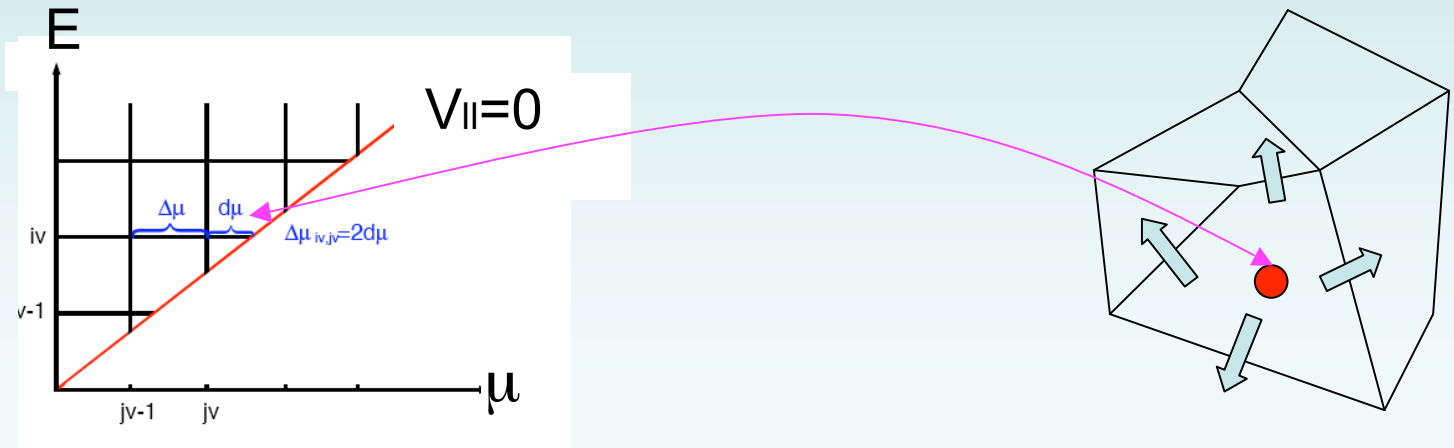


- Theory: [Rognlien & Cutler NF 20, 1003 (1980), Cohen NF 19, 1295 (1979); Najmabadi et al NF**24**, 75 (1984).]:
- $\tau = \tau_p + \tau_{fl}$

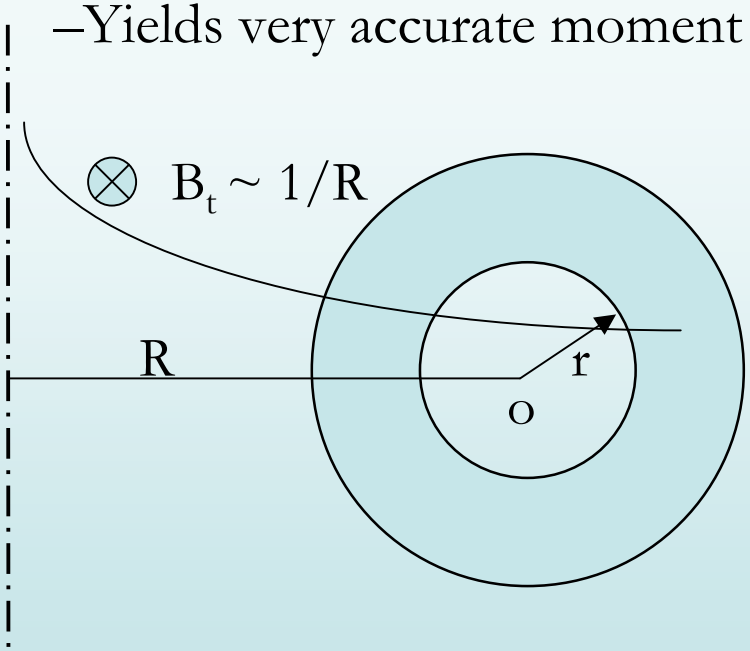


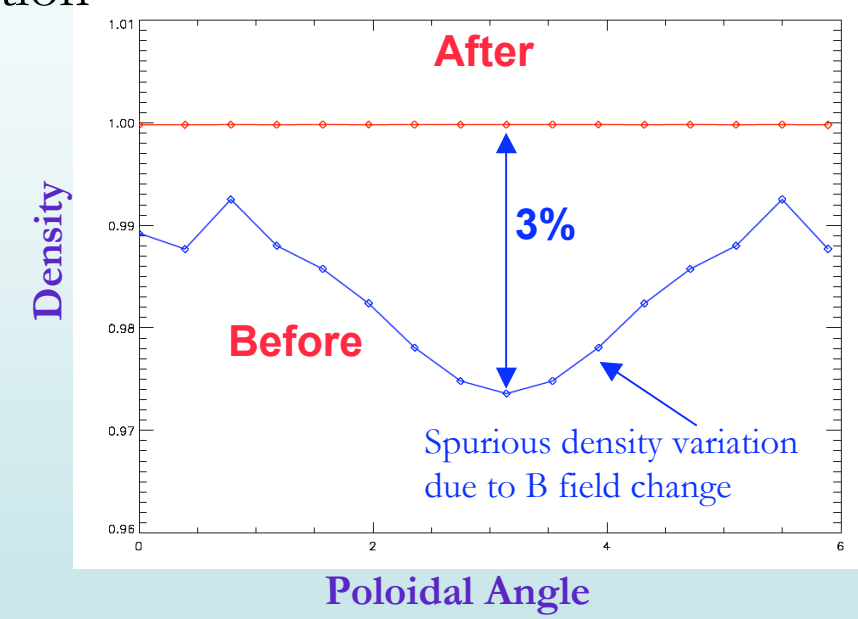
Cutcells and Finite Volum

- Velocity space finite volume method, conservative flux difference.
  - –Requires treatment of *cut cells* at turning point boundary



  - –Yields very accurate moment calculation





Geodesic-Acoustic Modes (GAM

- Axisymmetric mode (no toroidal variation)

  --- Parallel ion dynamics

  --- Magnetic curvature

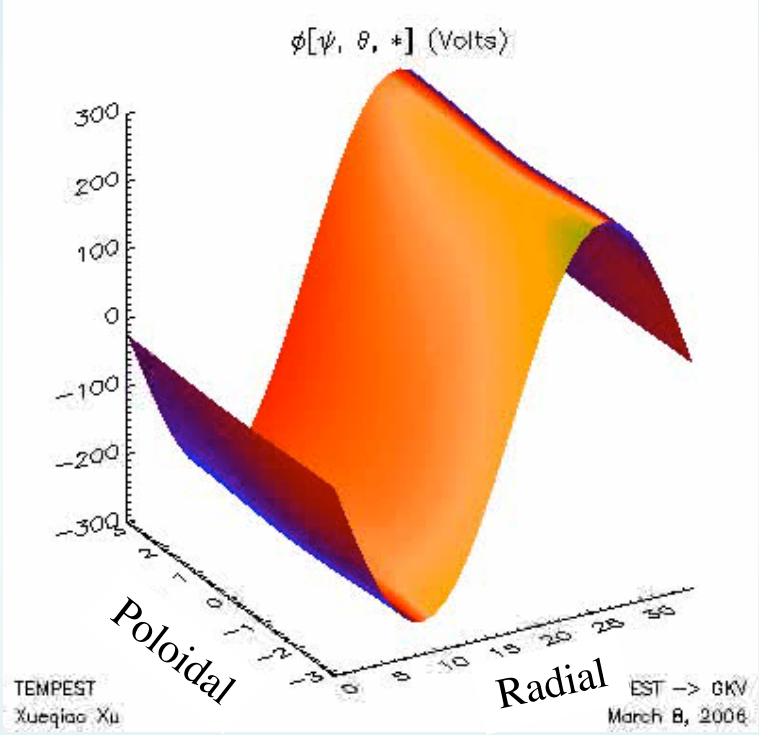
  --- TEMPEST should see GAM.

- Some GAM references in core plasma.

--- Lebedev et al, Phys. Plasma 3, 30023 (1996)

---- Rosenbluth & Hinton, PRL 80, 724 (1998)

---- Sugama & Watanabe, submitted to J. Plasma Phys. (2006)



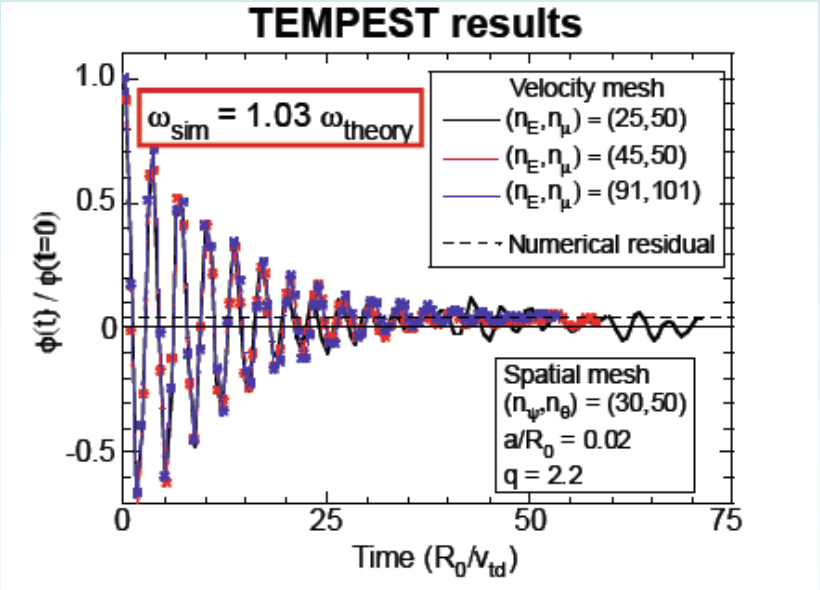
- Tempest solves gyrokinetic Poisson equation with Boltzmann electron models

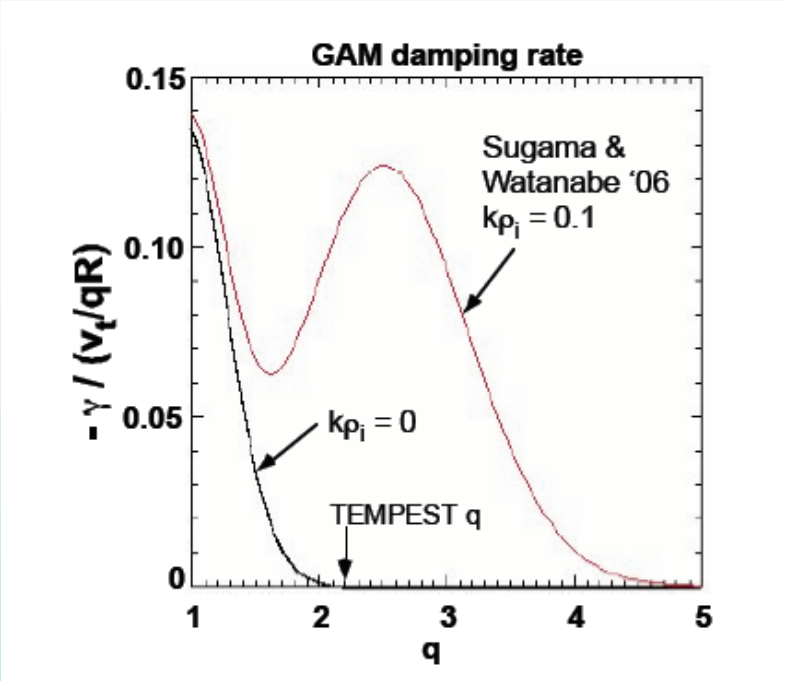
$$n_e(\theta,t) = A \exp(e\phi/T_e) / \langle \exp(e\phi/T_e) \rangle_\theta$$

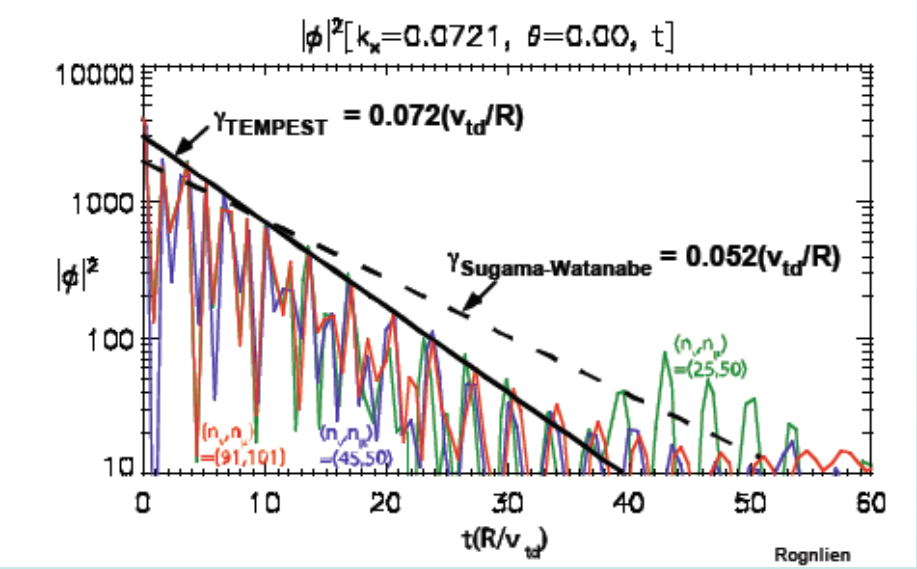
- Test streaming, radial drift, acceleration, field solve, and moments

Damping of the GAM follows theory

- Initial 2D fixed n_e pertubation cause ions/poten. to relax as GAM
- Sugama, Watanabe show damping sensitive to $k\rho_i$ at large q (bananas)
- TEMPEST example follows the larger damping from finite $k\rho_i$ and q

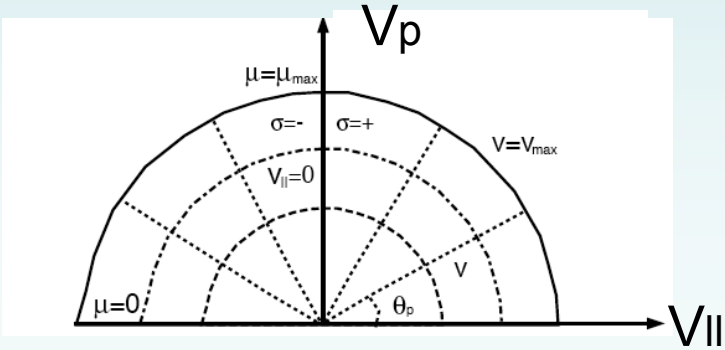


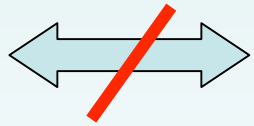


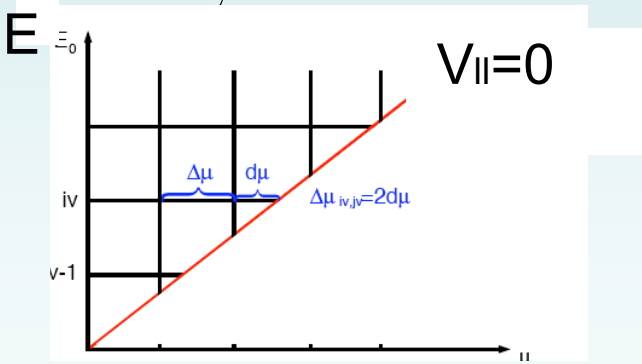


Linearized FPC in (E, μ

- **Goal: conservation and accuracy in collision operator**
  - –Finite volume is inherently conservative.
  - –Avoid numerical interpolation between different velocity coordinates .

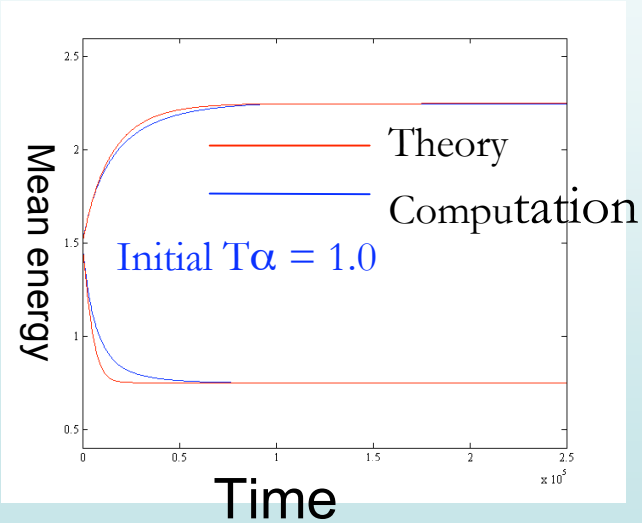






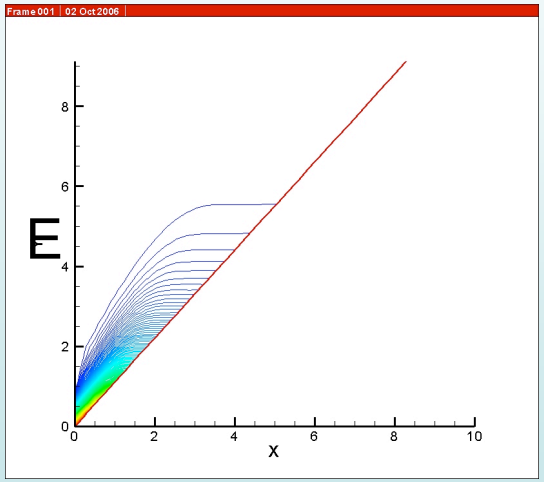
Linearized Fokker-Planck collision operator in (E, **μ**) space

Thermalization

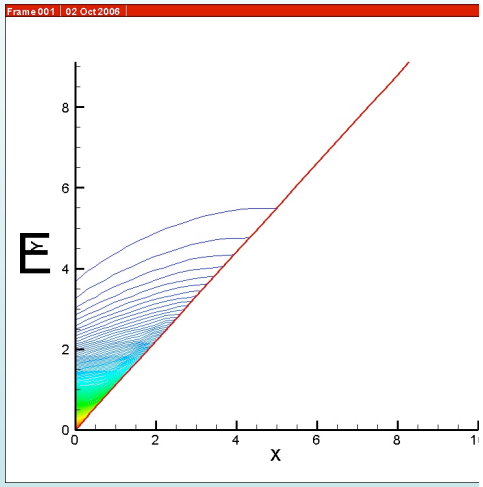


Filling Loss Cone

T1



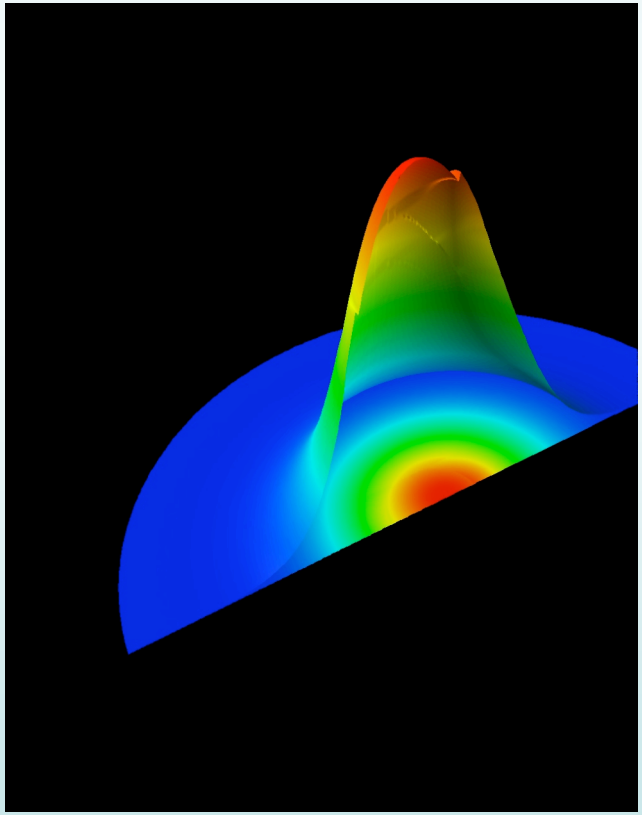
T2



Nonlinear FPC in (E, μ

- Same numerical framework as the linearized FPC in (E, μ)
- But the diffusion coefficients (Rosenbluth potentials) are computed from CQL package.
- Drifting Maxwellian test: Nonlinear self-collision annihilation.
- Inititial (subscript 0) and after 3 collision time (Subscript 1)

F

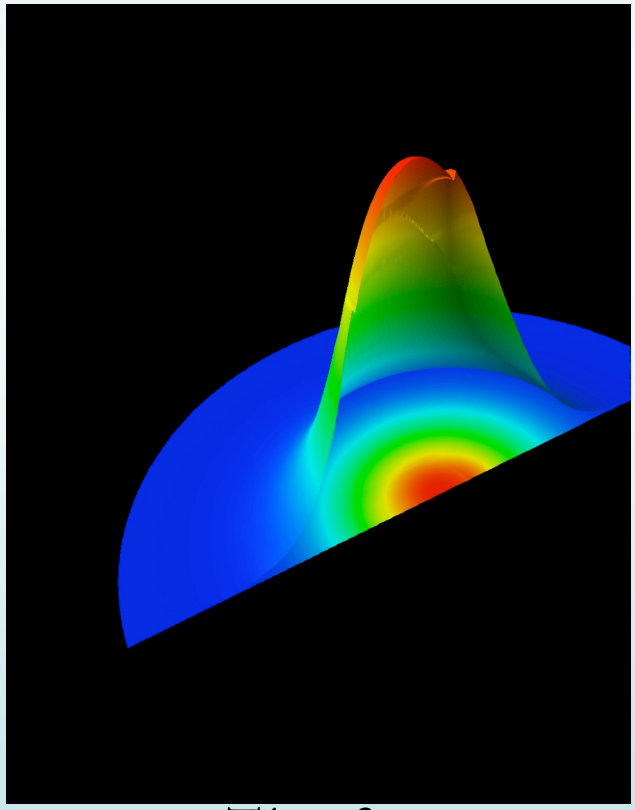


T0 = 0

Density
N0 = 0.99813
N1 = 0.99813

Momentum
U0 = 0.099847
U1 = 0.100249

Energy
E0 = 1.51792
E1 = 1.51564



T1 = $3\tau_{ii}$

Summary

- 4D TEMPEST results compared with analytic theory in collisional endloss and neoclassical flows in ring and divertor geometry

- Simulation of GAM agrees with analytic theory both in frequency and the damping rate.

- A new high-order finite volume method developed in (E, μ) space, and Poisson field solver with Boltzmann electron models implemented (See poster: JP63, M. Dorr, et al)

- A new nonlinear Fokker-Planck collision operator combining the finite volume scheme and the CQL package implemented. Drifting Maxwellian tests show good accuracy and conservation properties (See poster: Jp62, G. Kerbel et al).