Nonlocal Closures for Plasma Fluid Simulations

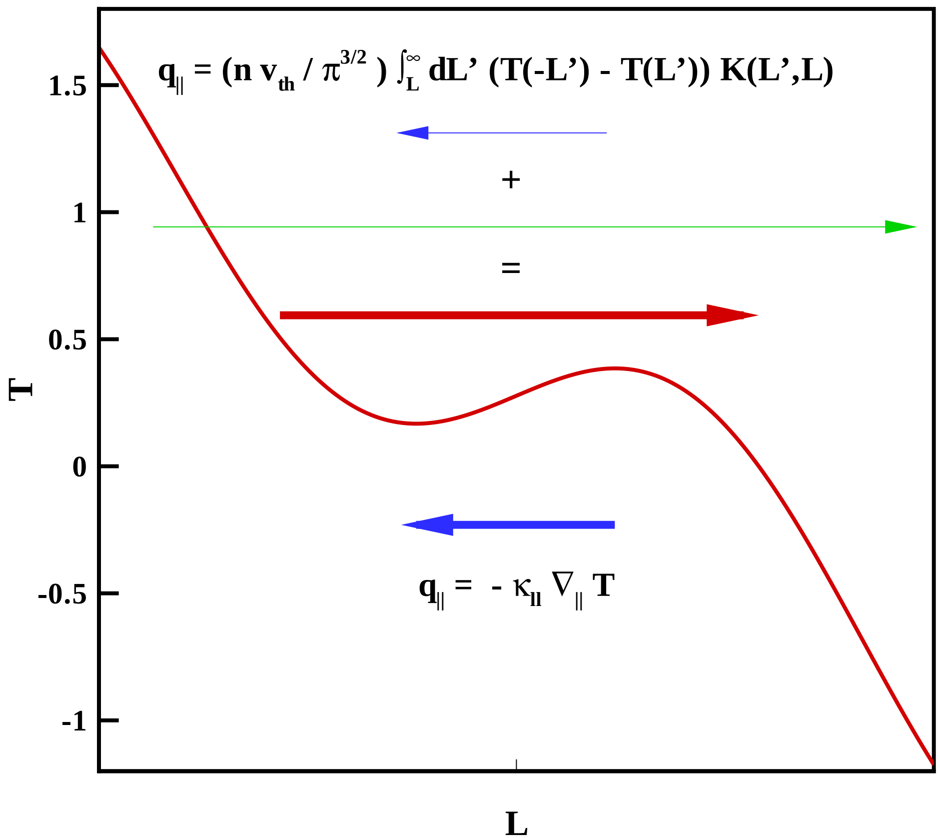
E. D. Held

eheld@cc.usu.edu

Utah State University

Nonlocal effects critical for getting correct $q_{\|}$.

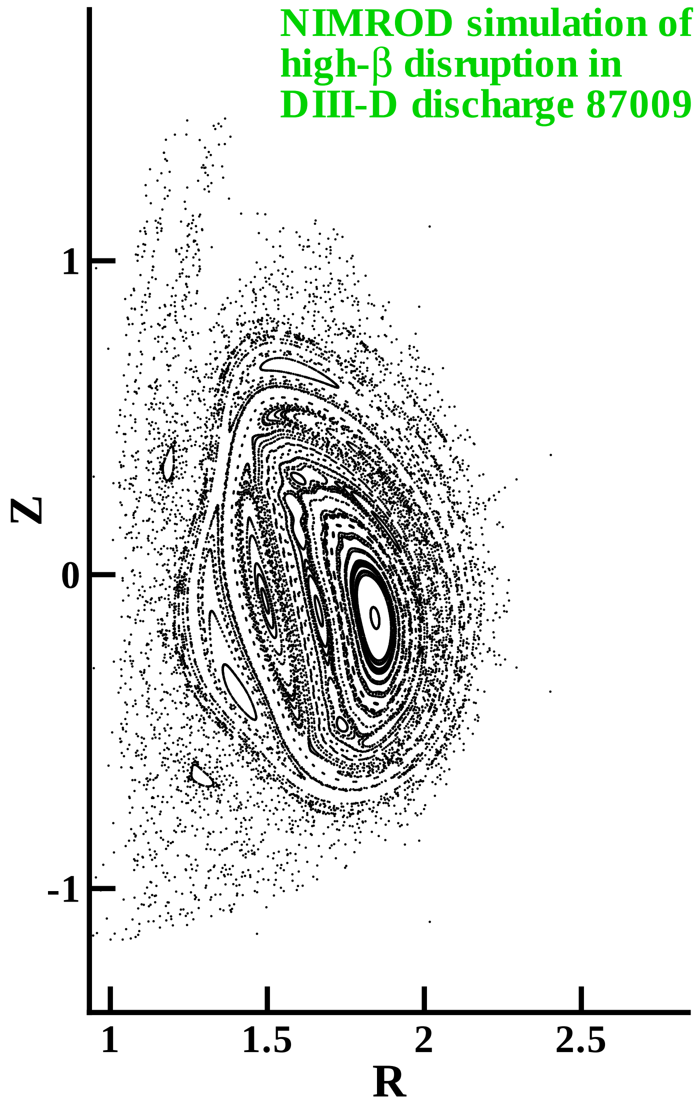
- Generalized $q_{\|}$ addresses nonlocal T perturbations for robust flattening.

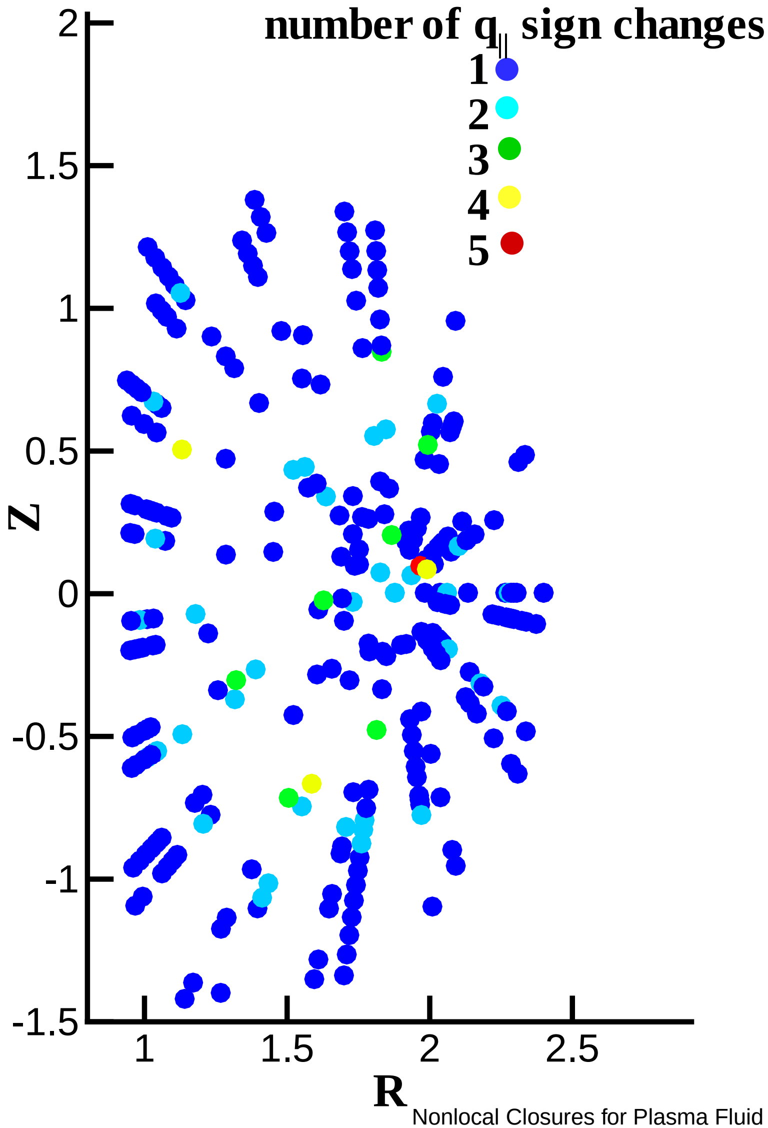


- Diffusive $q_{\|}$ addresses local gradient only getting wrong sign and magnitude.

Nonlocal effects critical for getting correct $q_{\|}$.

- Overlapping magnetic perturbations lead to field line chaos which emphasizes nonlocal effects of $q_{\|}$ closure.

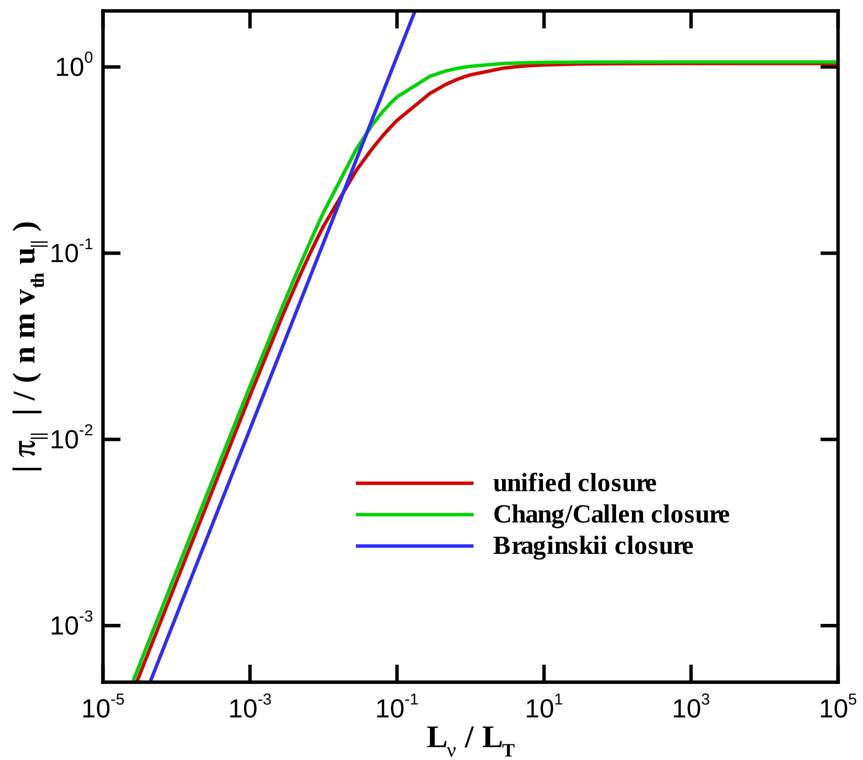




Analogous nonlocal $\pi_{\|}$ exists for sheared slab geometry [10]*.*

$$\mathbf{K}_1{}^1(U_{\|}) + \mathbf{K}_{12}(\pi_{\|}) = \int_0^{\infty} d\bar{L}\,\left(u_{\|}(L+\bar{L}) + u_{\|}(L-\bar{L})\right) \frac{\partial K_1(\bar{L})}{\partial \bar{L}} + B_1 u_{\|}(L),$$

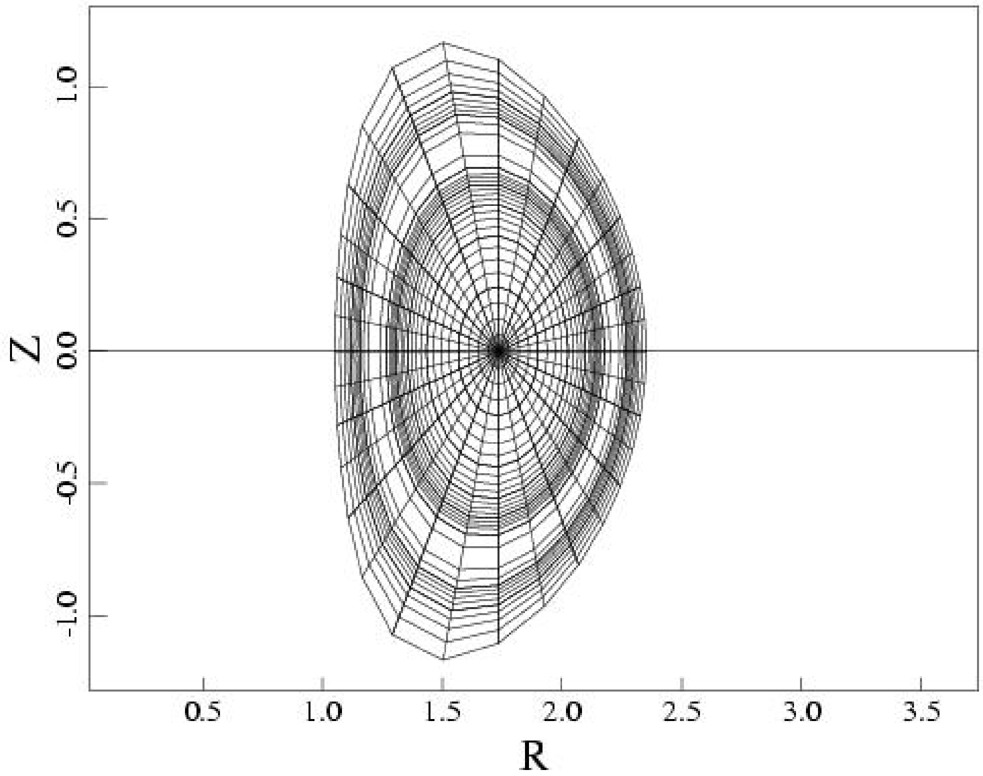
$$\mathbf{K}_{21}(U_{\|}) + (1+B_2)\pi_{\|} + \mathbf{K}_{22}(\pi_{\|}) = \int_0^{\infty} d\bar{L}\,\left(u_{\|}(L+\bar{L}) - u_{\|}(L-\bar{L})\right) \frac{\partial K_2(\bar{L})}{\partial \bar{L}}.$$



10 E. D. Held, *Generalized form for parallel ion viscous stress in magnetized plasmas, to be published in Phys. Plasmas* (2003).

Implement $q_{||}$ using massively parallel approach.

- NIMROD code [11] uses finite elements in poloidal plane and Fourier decomposition in toroidal angle.
- Bi-quartic finite elements on 32 X 32 grid with 3 toroidal modes requires $\approx 10^5$ $q_{||}$ calculations $\Rightarrow$ hundreds of processors.



11 C. R. Sovinec, *et al., Nonlinear Magnetohydrodynamics Simulation using High-Order Finite Elements, accepted in J. Comp. Phys. (2003).*

Avoid time step limitation by using semi-implicit advance for T.

- Easily inverted anisotropic heat diffusion operator stabilizes T advance:

$$[\,\mathbf{I} - \Delta t f \overbrace{\left(\vec{\nabla}\cdot\kappa_\perp\vec{\nabla}_\perp + \vec{\nabla}\cdot(\kappa_\| - \kappa_\perp)\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\vec{\nabla}\right)}^{\text{anisotropic diffusion}}\,]\,\Delta T =$$

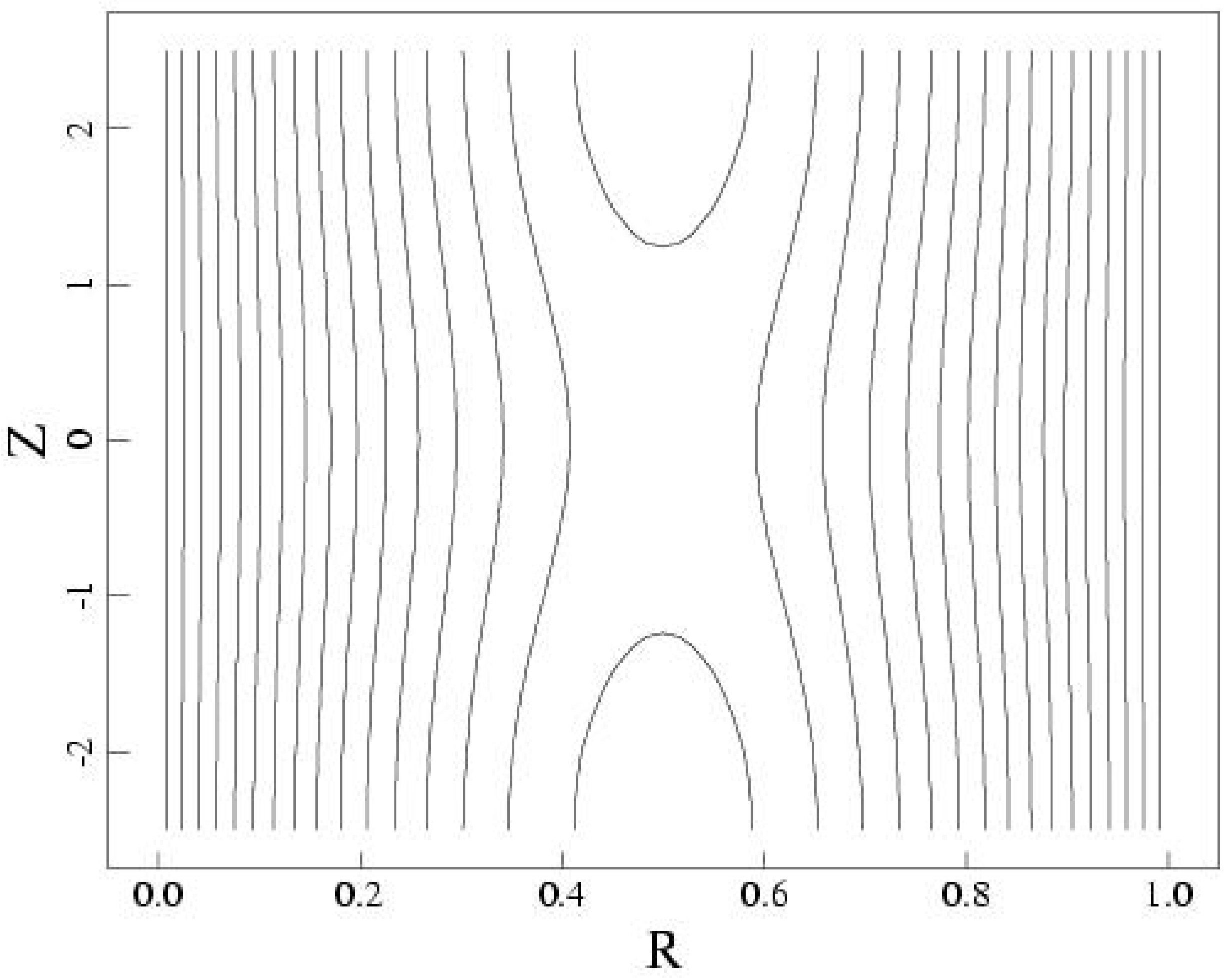
$$\Delta t\,[\,\kappa_\perp\nabla^2 T - \vec{\nabla}\cdot\kappa_\perp\hat{\mathbf{b}}\hat{\mathbf{b}}\cdot\vec{\nabla}T + \underbrace{\vec{\nabla}\cdot\vec{q}_\|}_{\substack{\text{explicit}\\ \text{nonlocal}\\ \text{closure}}}\,]\,.$$

- Minimum value of centering parameter, f, exists such that advance is stable for any time step, Δt.

Avoid time step limitation by using semi-implicit advance for T.

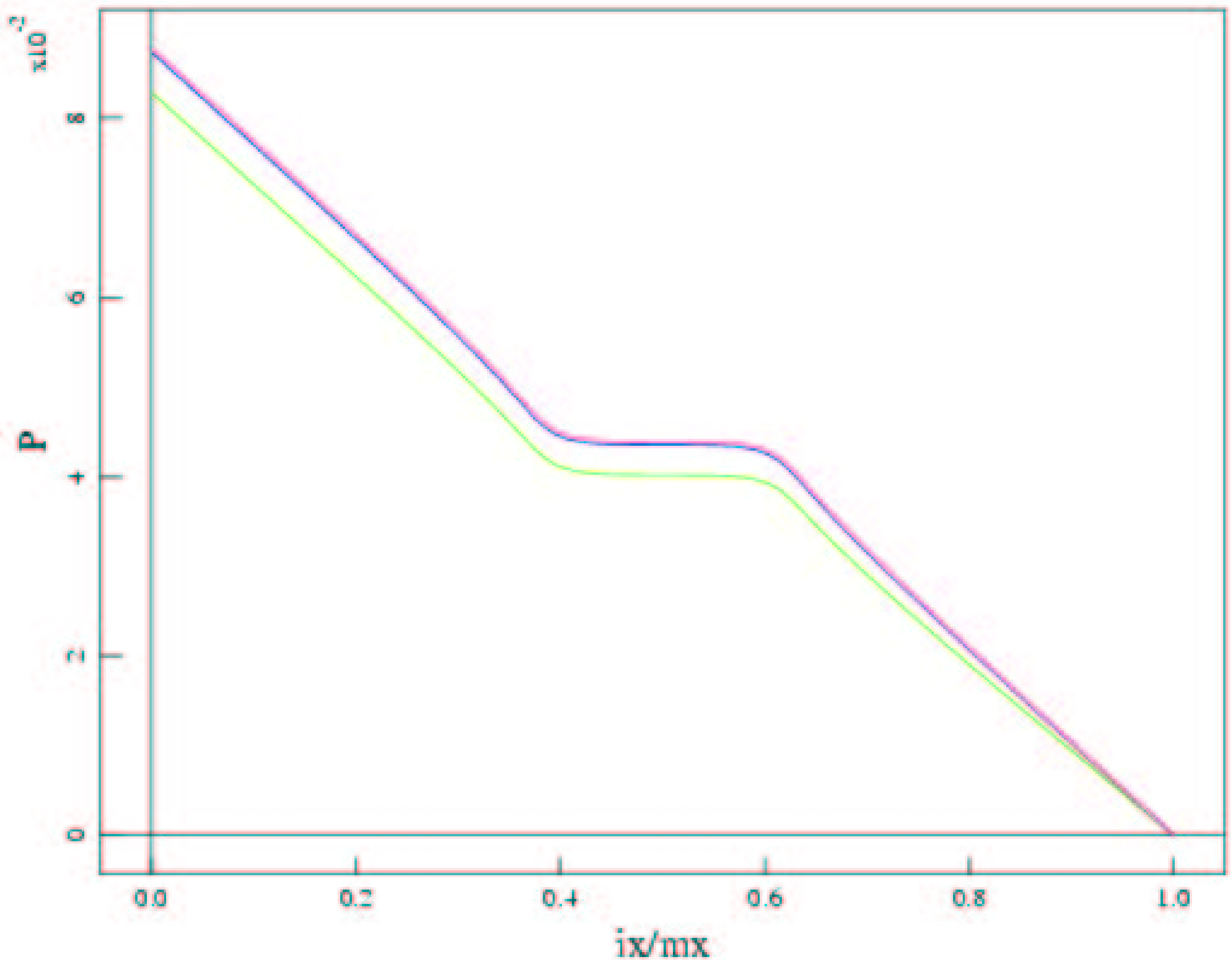
- Test semi-implicit time advance in frozen slab island geometry.

applied
heat
flow
$\rightarrow$



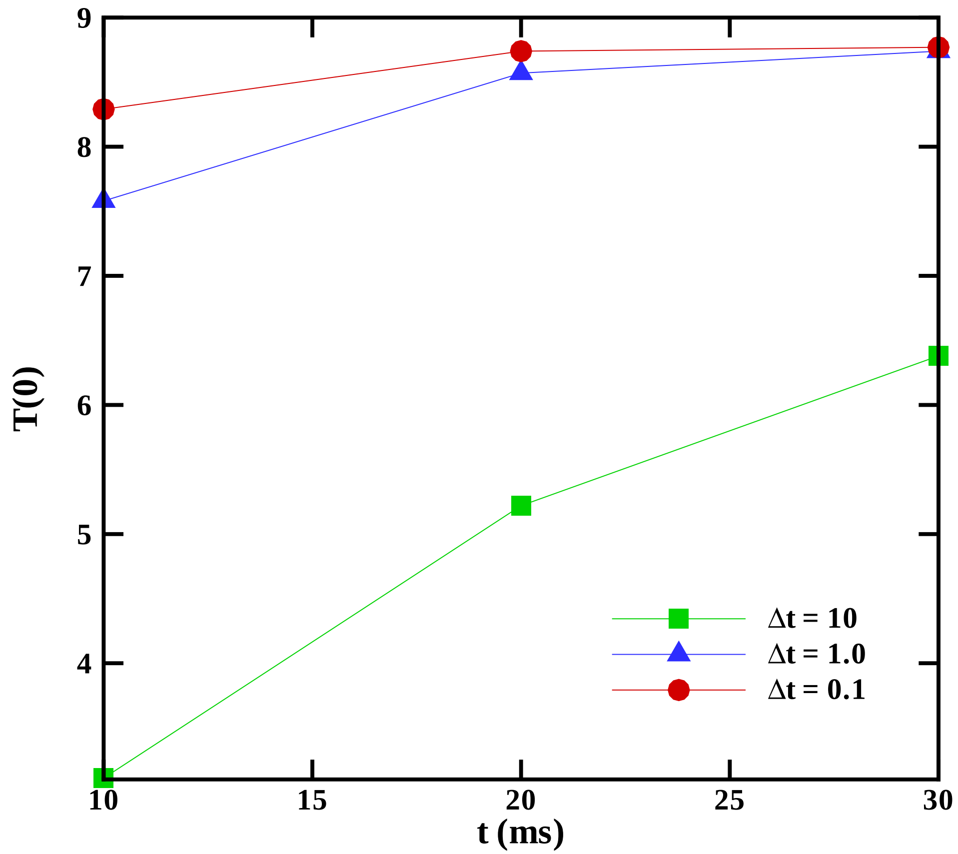
Avoid time step limitation by using semi-implicit advance for T.

- Significant flattening across O-point with $T_0 = 1$ keV and $\Delta t = 0.1$ ms.



Avoid time step limitation by using semi-implicit advance for T.

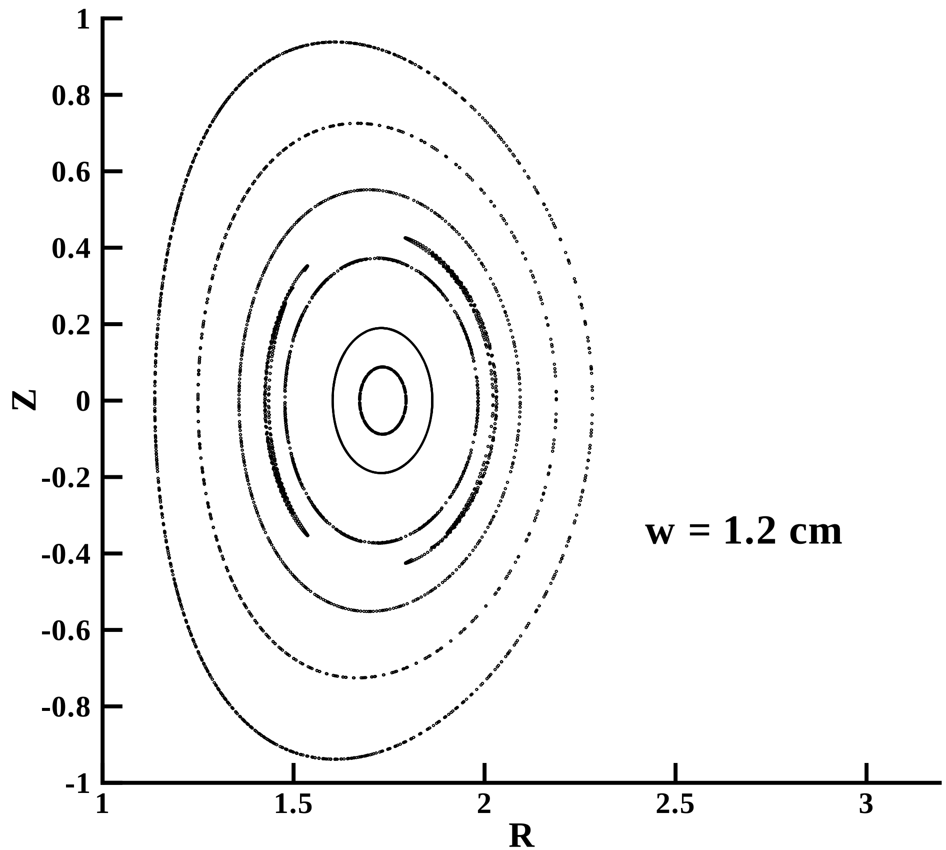
- T evolution converges as Δt is reduced.



- Combination of generalized closure theory and massively parallel numerics permits simulation of parallel particle dynamics on fluid time scales.

Apply $q_{\|}$ to study heat flow dynamics in tokamaks.

- Evolve T in frozen geometry to determine island width when T contours begin to coincide with flux surfaces, *i.e.*, when T flattens across island O-point.



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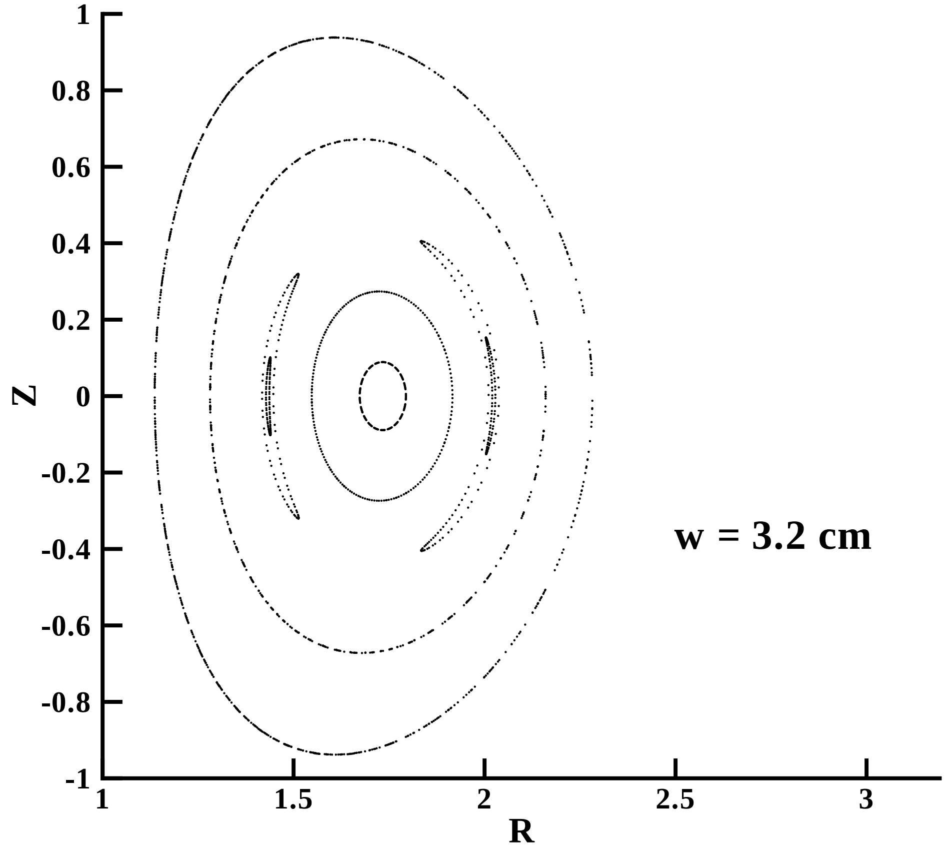

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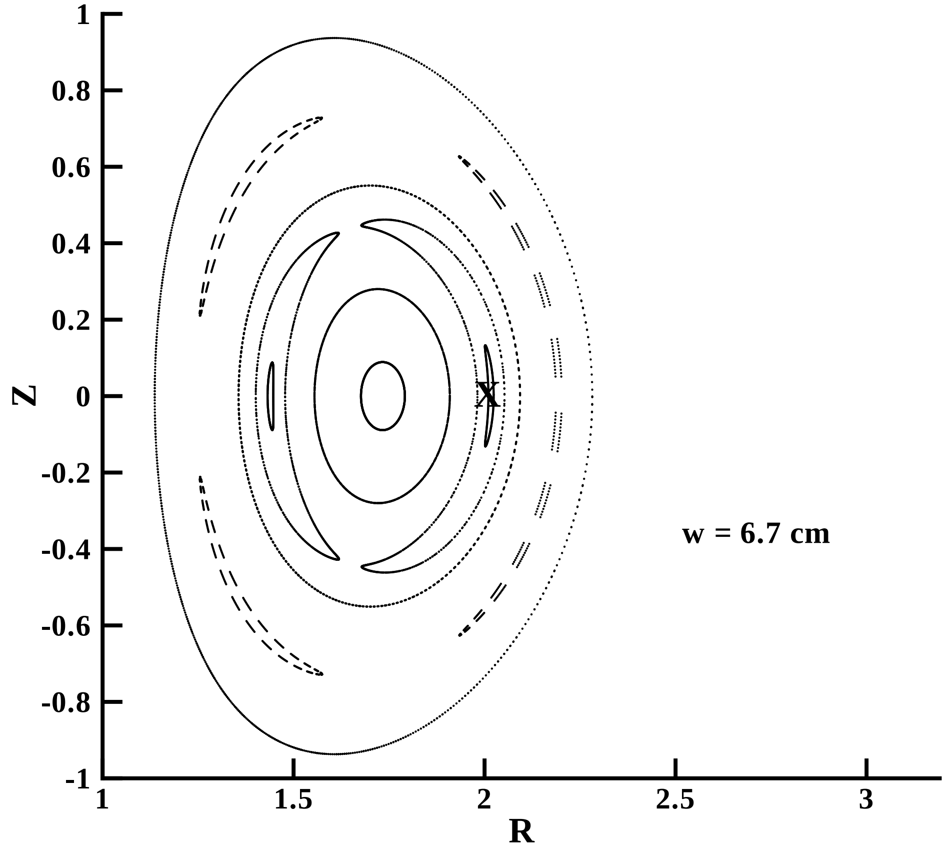
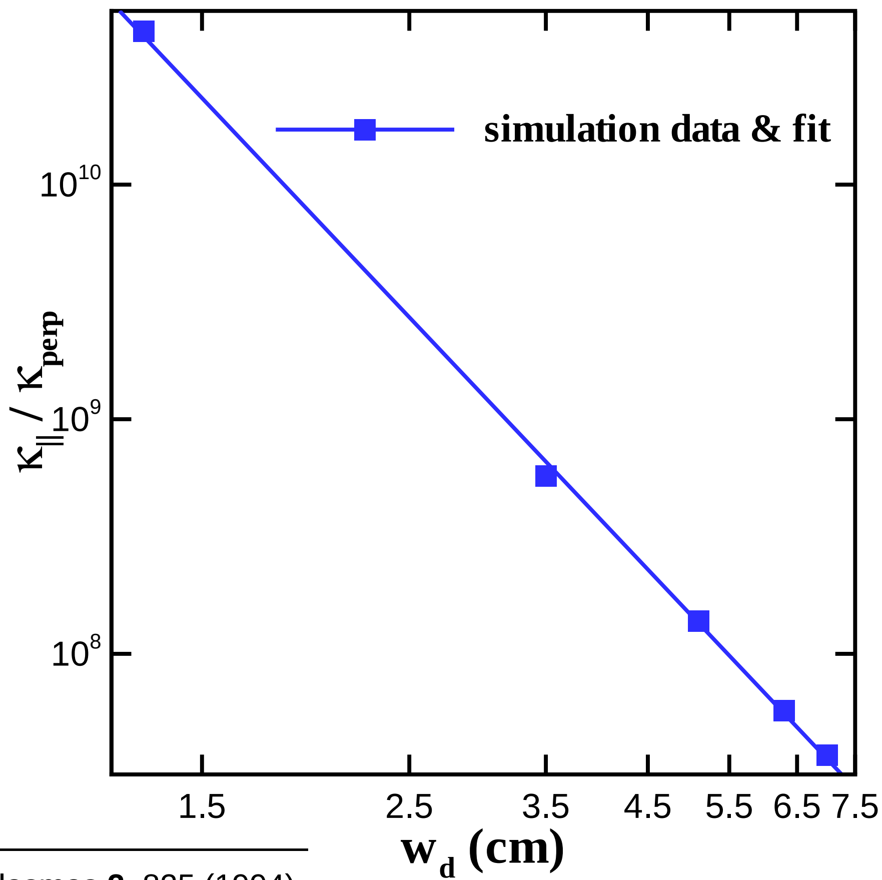


Large $\kappa_\parallel/\kappa_\perp$ needed for flattening with diffusive $q_\parallel$.

- Cylindrical, diffusive analytical scaling[12] $\kappa_\parallel/\kappa_\perp \sim w_d^{-4.0}$.
- Toroidal, diffusive numerical scaling[13] $\kappa_\parallel/\kappa_\perp \sim w_d^{-4.2}$.

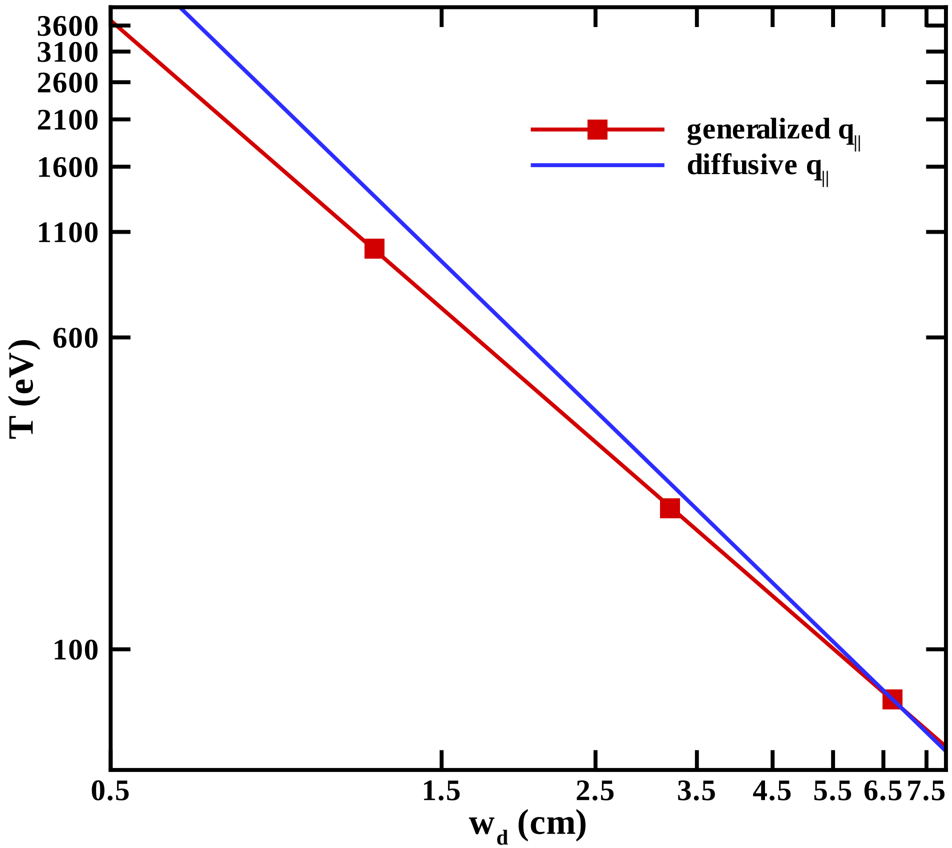


12 R. Fitzpatrick, Phys. Plasmas **2**, 825 (1994).

13 C. R. Sovinec, T. A. Gianakon, E. D. Held, S. E. Kruger and D. D. Schnack, Phys. Plasmas **10**, 1727 (2003).

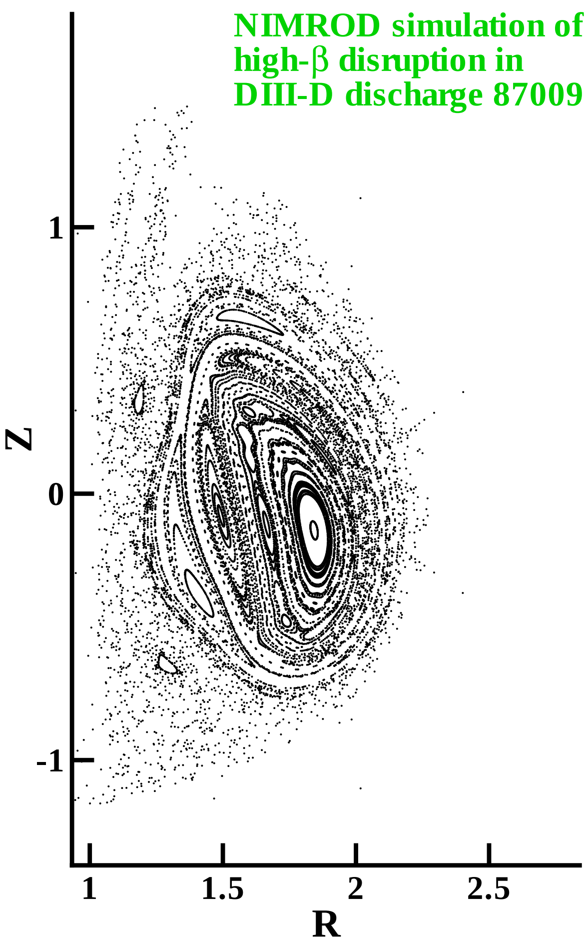
Generalized $q_{\parallel}$ predicts more robust flattening.

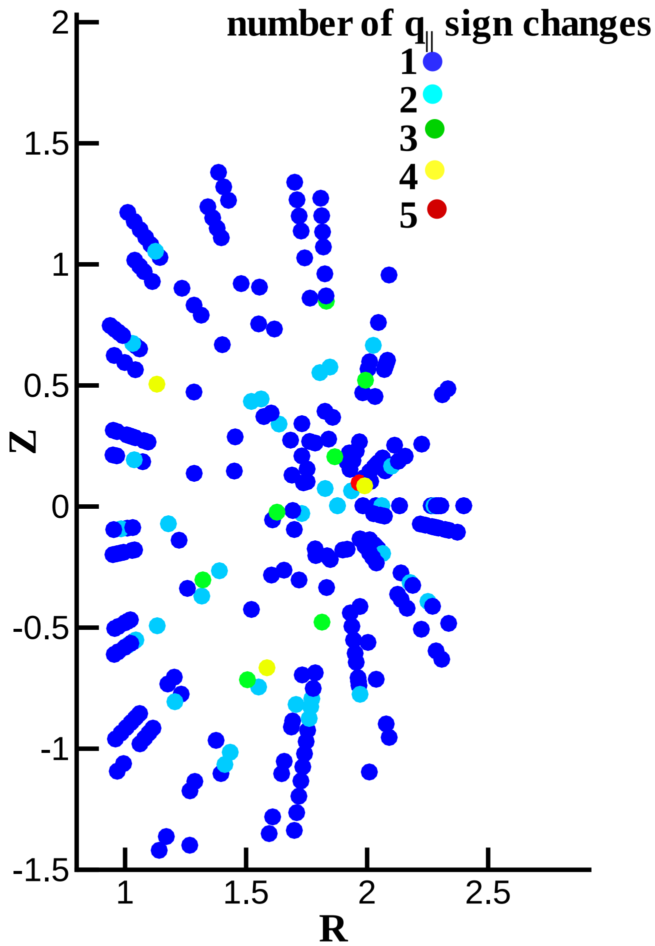
- Cylindrical, diffusive analytical scaling with[12] $\kappa_{\parallel} \sim T^{5/2}$, $T \sim w_d^{-1.6}$.
- Toroidal, diffusive numerical scaling[13] $T \sim w_d^{-1.7}$.
- Generalized numerical scaling $T \sim w_d^{-1.5}$.



Nonlocal $q_{\|}$ useful in disruption simulations.

- Simulation of disruption in DIII-D shot 87009 [14] results in field line chaos.

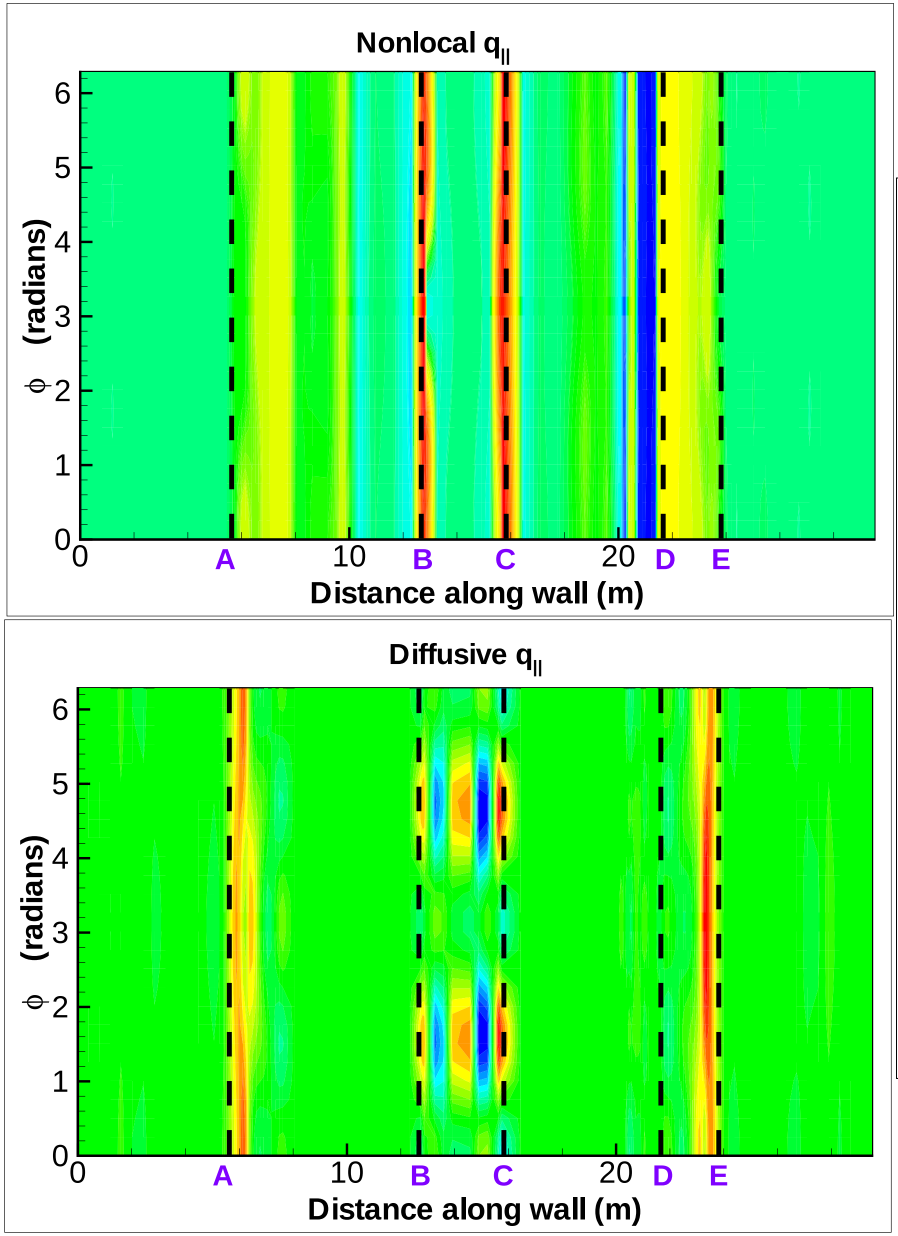


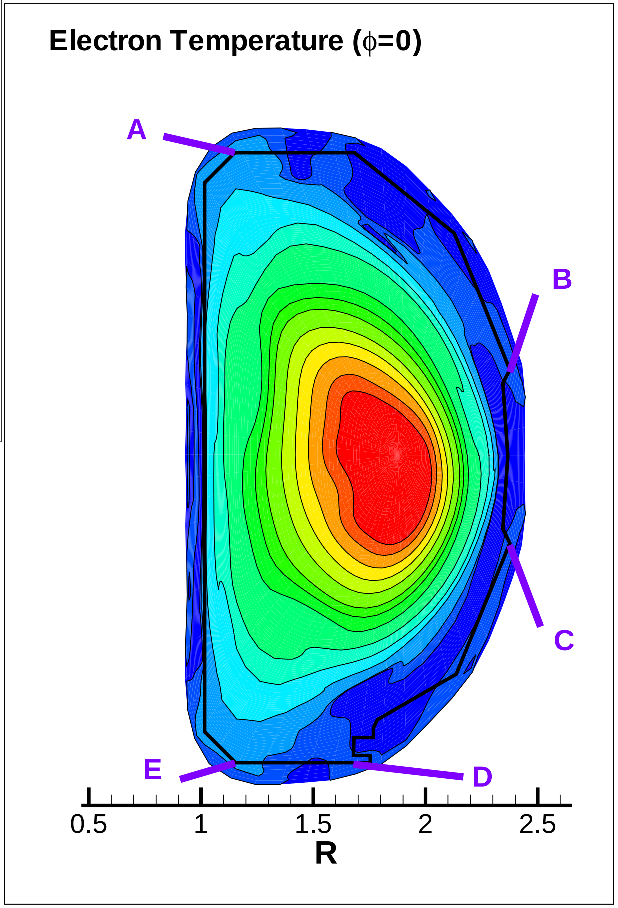


14 J. D. Callen, *et al.*, Phys. Plasmas **6**, 2963 (1999).

Nonlocal closure qualitatively different than diffusive closure.

- Heat flows rapidly along field lines hitting the wall.





Conclusion

- Developed nonlocal closures that encompass Landau, collisional, and particle trapping physics in general toroidal geometry.
- Implemented massively parallel semi-implicit approach in NIMROD code for application to high-performance, toroidal fusion experiments.
- Combination of generalized closure theory and massively parallel numerics permits simulation of parallel particle dynamics on fluid time scales.
- Scaling of $T \sim w_d^{-1.5}$ for nonlocal $q_{||}$ predicts robust flattening of temperature across magnetic islands.
- Preliminary application of nonlocal $q_{||}$ in disruption simulations reproduces qualitative features of wall heat loads.

Acknowledgments

- Collaborators:
  J. D. Callen, C. C. Hegna, and C. R. Sovinec, U. of Wisconsin,
  T. A. Gianakon, Los Alamos National Laboratory,
  S. E. Kruger and D. D. Schnack, SAIC,
  the NIMROD Team, and
  the Center for Extended Macroscopic Modeling.
- This research has been supported by DOE under grant no. DE-FG03-01ER54618.