INITIAL RESULTS FROM THE NEW EDGE SIMULATION LABORATORY CODE

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Edge
Simulation
Laboratory

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ABSTRACT

The Edge Simulation Laboratory (ESL) project is developing continuum-based approaches to kinetic simulation of edge plasmas. A new code is being developed, based on a conservative formulation and fourth-order discretization of full-f gyrokinetic equations in parallel-velocity, magnetic-moment coordinates. The code exploits mapped multiblock grids to deal with the geometric complexities of the edge region, and utilizes a new flux limiter[1] to suppress unphysical oscillations about discontinuities while maintaining high-order accuracy elsewhere. The code is just becoming operational; we will report initial tests for neoclassical orbit calculations in closed-flux surface and limiter (closed plus open flux surfaces) geometry. It is anticipated that the algorithmic refinements in the new code will address the slow numerical instability that was observed in some long simulations with the existing TEMPEST code. We will also discuss the status and plans for physics enhancements to the new code.

[1] P. Colella and M.D. Sekora, JCP 227, 7069 (2008).

OUTLINE

edge
simulation
laboratory

- ESL at a glance
- Spiral design: TEMPEST was the first spiral
  - Lessons learned; things we sought to do better with ESLCode
- ESL Code design features
- Code tests
- Current capability
- What's in progress (but miles to go…)

- NOTE ADDED 5/15/09: at the time of Sherwood, running with a toroidal limiter was still in debug phase. In the process we found an error which gave the wrong sign for the curvature drift. This has been corrected but is not reflected in the plots shown in the test cases; primarily, the banana orbit test now shows a somewhat fatter banana, as expected. Corrected plots, along with results from the toroidal limiter test, will be shown at the ESL workshop 5/20/09.

What is the ESL?

- Edge Simulation Laboratory (ESL): a project to develop gyrokinetic simulation for MFE edge plasmas based on continuum (Eulerian) techniques
- Why continuum?
  - Concerns about PIC noise in environment where there are large density variations and where full f is required
  - Exploit advanced numerical methods from fluids community
  - Build on successes of continuum core codes (GYRO, GS2, GENE)
- ESL is a collaboration: LLNL, GA, UCSD, LBNL, PPPL, Lodestar. Others welcome.

ESL has had three funded components

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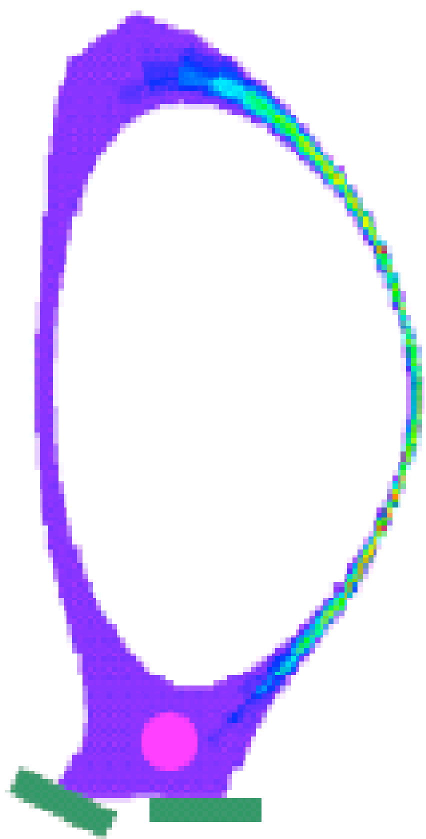
- TEMPEST code (outgrowth of LLNL LDRD project; full geometry, full-f, ε -μ finite difference.)
- GA rapid-prototype codes, EGK ($v_{||}$-μ), NEO ($v_{||}/v$, ε_k), simple geometry (no separatrix); presently linear
- Math component: develops and implements algorithms for a next-generation code; develops kernel of the new code.
- These efforts are starting to merge -- LLNL physicists have started to work with the new code ("ESLCode") and are adding content.

TEMPEST is a full-f, full-geometry edge kinetic code

- 5D (ψ,θ,ζ,E_0,μ); results here 4D
  - E_0-μ choice for accurate || streaming
- Full f, but also δf option
- Electrostatic (EM deferred to next gen. code)
- Geometry options:
  - Shifted circle core
  - Full single-null diverted, closed-flux-surface + SOL
- Implicit backward-differencing time advance; Newton-Krylov iteration
- 4th-order upwinded finite-difference spatial discretization, and Weno
- Low-order finite-volume discretization for collisions
- Collision options
  - Krook
  - Lorentz with full v dependence
  - Full collision op. with test-particle or fully nonlinear Rosenbluth potentials



We learned lessons from TEMPEST

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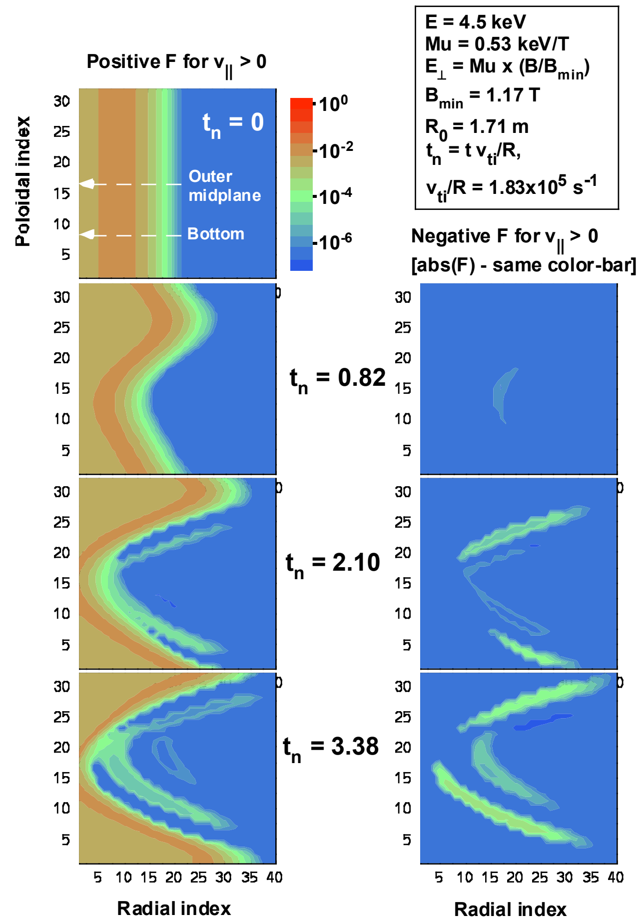
- TEMPEST is producing interesting physics (see e.g. Xu's poster at this meeting) but has presented many challenges
  - E, μ coordinates ⇒ multiple sheets (+,- $v_{||}$) and cut-cell boundaries
    - Finite discretization and different treatment of $v_{||}$ and drifts can produce small advection across the $E_{||} = 0$ boundary
  - Non-conservative formulation ⇒ challenge to get sufficient accuracy for field solve
  - Instabilities observed sometimes, especially (but not exclusively) in divertor geometry. Growing negative spikes of n and/or T.
    - Starts with a growing region of negative f
      - (example is from circular core geometry with 10:1 n and T variation)



The new ESL code builds on experiences from TEMPEST, EGK, Neo, and core codes

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- Conservative form of GK equations
- 4th order finite-volume (conservative) discretization,independent of grid choice
  - e.g. no loss of accuracy order in going to non-uniform grid
- $v_{||}$-μ coordinates (initially)
- Arbitrarily mapped multiblock grids, field-aligned on blocks (allowing for shifts at any box boundary), to handle geometric complexity of edge (x point, magnetic shear).
- Colella-Sekora flux-limiter to suppress unphysical oscillations about discontinuities while maintaining high-order accuracy elsewhere
- AMR capability eventually -- built directly on Chombo.
- Electrostatic initially; subsequently EM

Past experience leads to requirements and numerical methodologies to address them

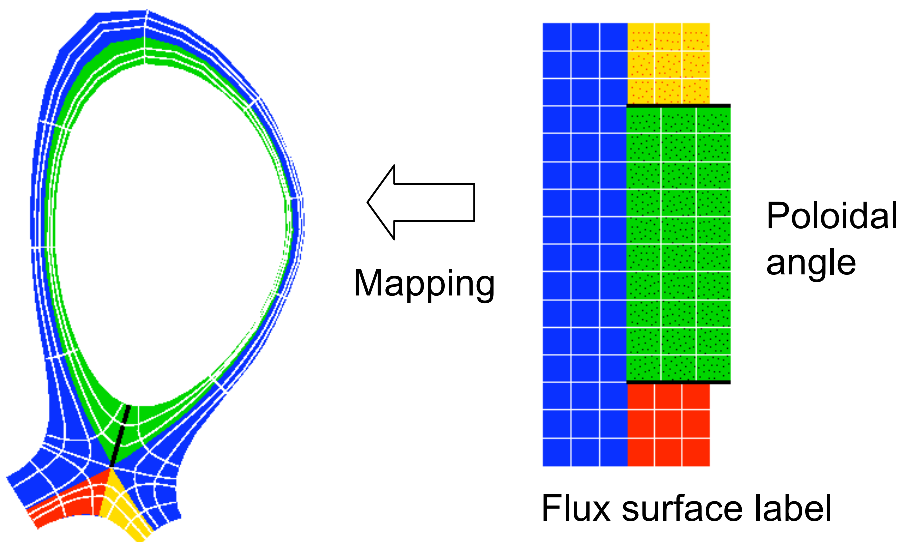
Requirements:

- Conservation
- Low-dissipation advection
- Preservation of distribution function positivity
- Efficient resolution of a large and complicated phase space
- Robust for high anisotropy
- Efficient implicit solves

Numerical methodologies:

- Finite volume discretizations applied to conservative formulations
- High-order discretization
- Mapped, multiblock grids*
- Preconditioned iterative methods

* Mapped means results of vector operations in cartesian x,y,z mapped onto faces of near-field-line-aligned grids. Multiblock means arbitrary connectivity of discrete blocks of cells



We are developing high-resolution discretizations for the gyrokinetic Vlasov equation

- The gyrokinetic Vlasov equation describes advection by a phase space velocity field that is a nonlocal function of the distribution function f :

$$\frac{\partial f}{\partial t} + \boldsymbol{\nabla}_{\boldsymbol{R}} \cdot \left(\dot{\boldsymbol{R}}(f) f \right) + \frac{\partial}{\partial v_{\parallel}} \left(\dot{v}_{\parallel}(f) f \right) = 0$$

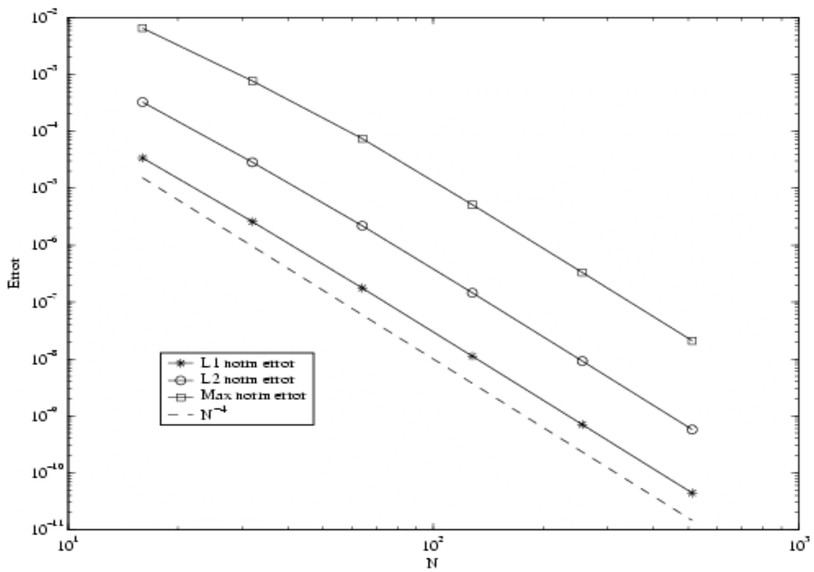
- Dependence of the phase space velocities $\dot{\boldsymbol{R}}$ and $\dot{\boldsymbol{v}}_{\parallel}$ on f is through the Poisson solve
- To obtain a high-order discretization that is robust for this highly nonlinear system, we combine
  - fourth-order, multidimensional, flux-corrected transport (FCT) spatial discretization
  - fourth-order Runge Kutta time integration
- Based on a new PPM limiter (Colella-Sekora)
  - Preserves fourth-order accuracy where solution is smooth (does not reduce accuracy at smooth extrema like classical FCT and PPM)
  - Can be combined with an FCT multidimensional limiter (Zalesak) to preserve distribution function positivity

4^{th}-order accuracy of the GK Poisson discretization has been obtained on core equilibrium geometries

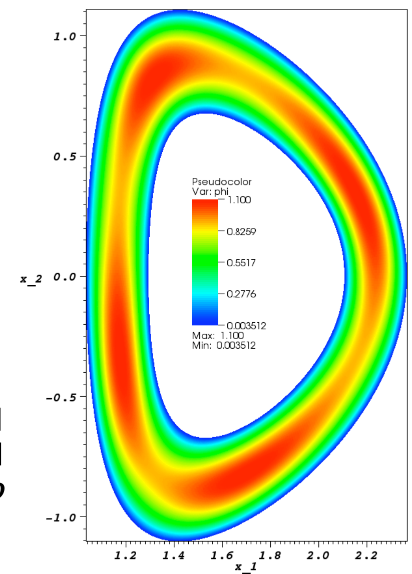
Given Φ, use high accuracy quadrature to manufacture ρ such that

$$\nabla \cdot \left\{ \left[\epsilon_0 \boldsymbol{I} + \frac{n_i}{B^2} \left(\boldsymbol{I} - \vec{b}\vec{b}^T \right) \right] \nabla \Phi \right\} = \rho$$

using a prescribed density profile n_i and a magnetic field from an analytically specified equilibrium model*.



Verification of 4^{th} order convergence



Potential computed from exact ρ

Convergence of *Hypre* CG solver preconditioned with multigrid solution of second-order operator

iter	Relative residual
1	6.62e-03
2	1.19e-03
3	2.24e-04
4	1.17e-04
5	4.59e-05
6	1.18e-05

*Miller et al., "Noncircular, finite aspect ratio, local equilibrium model", Phys. Plasmas, Vol. 5, No. 4 (1998).

We have begun a testing phase with the new code

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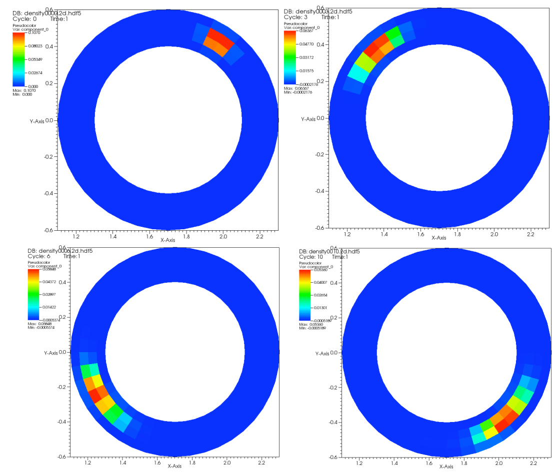
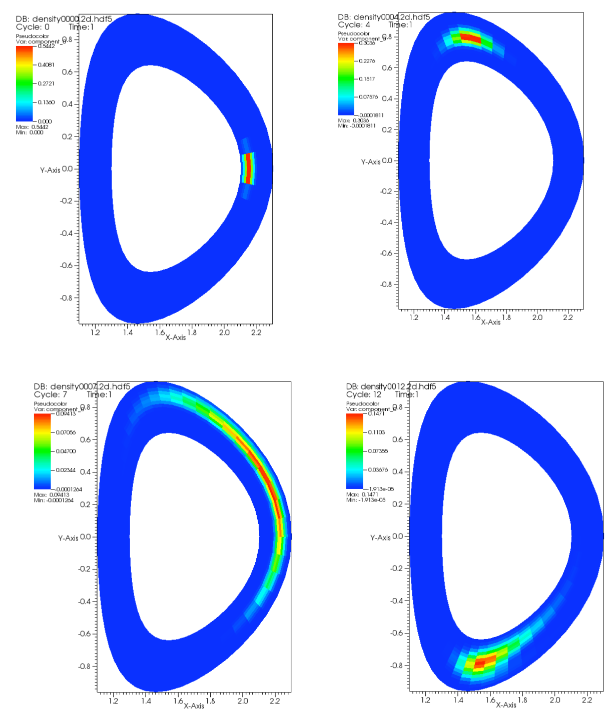
- Const. velocity advection in radial, poloidal directions: verified that localized phase-space blob transported at correct rate, without significant spreading beyond initial readjustment.



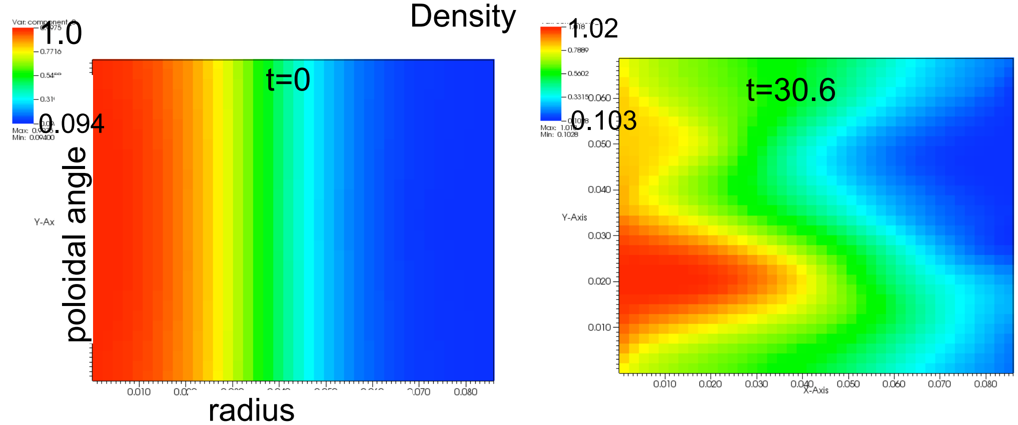
- Magnetic mirroring: using full kinetic equation with drifts off and on, verified that a localized blob of magnetically trapped plasma turns at correct poloidal angle, with correct banana width, in correct time (circular geometry). Observed spatial spreading ~ consistent with initial phase-space width.
- Repeated above in non-circular geometry



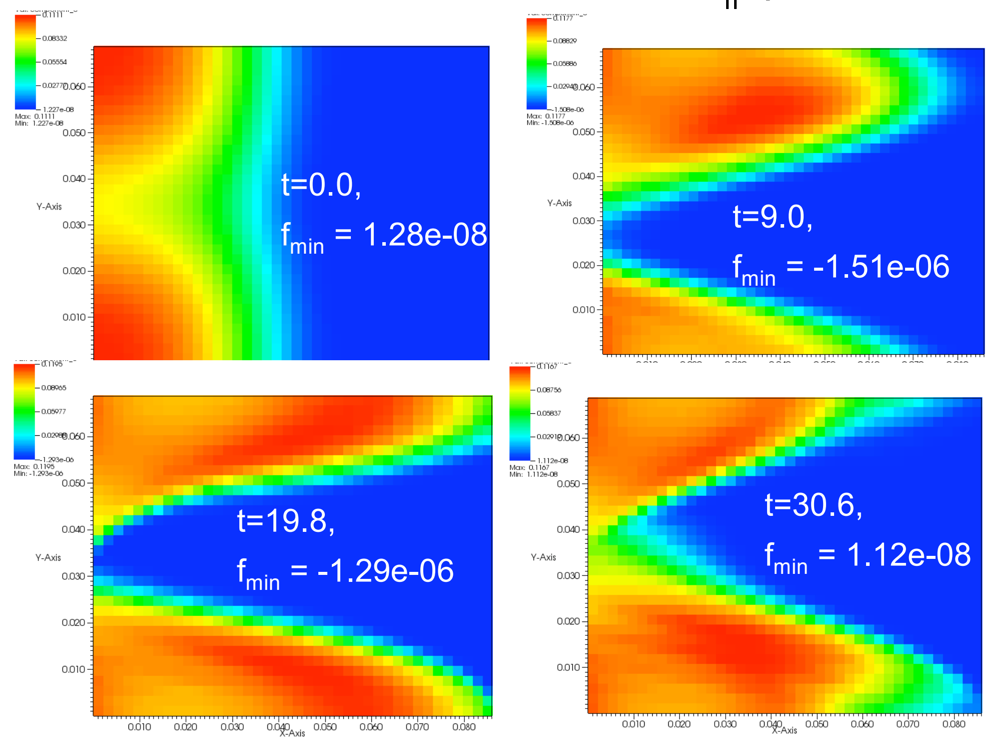
Collisionless evolution of steep tanh profiles indicates stable evolution

- Did experiment similar to the simplest TEMPEST case that exhibited instability: circular geometry, 10x decrease in T, n across annulus.
- GK advance uses Colella-Sekora flux limiting but not yet positivity-preserving
- Observed: phase-space regions with very small negative f but no evidence of instability.
- Next: repeat with toroidal limiter (now debugging); then turn on field solve

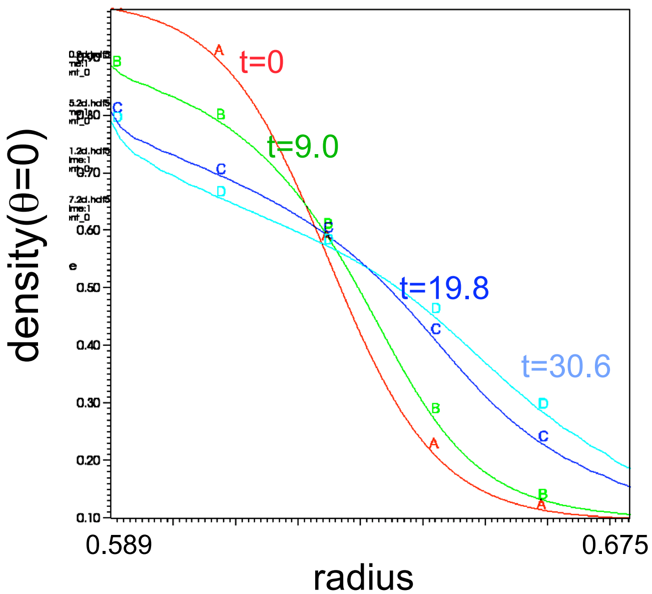
Density



Distribution fn. at fixed $v_{||}$, μ



More details from steep tanh profile run

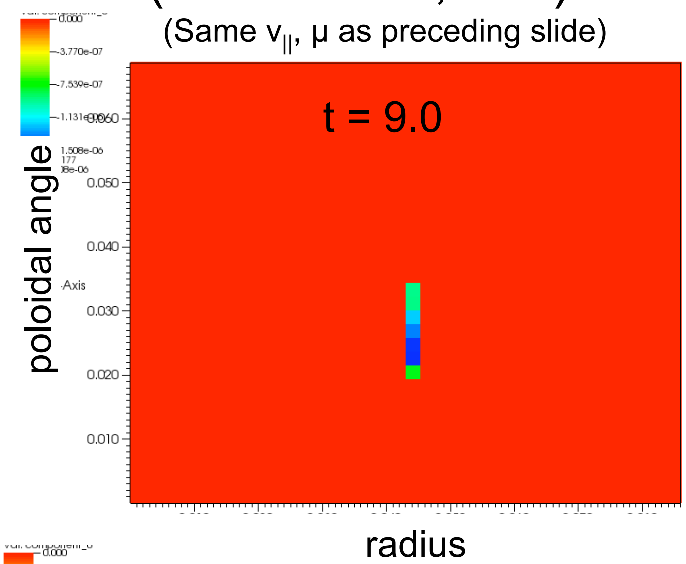


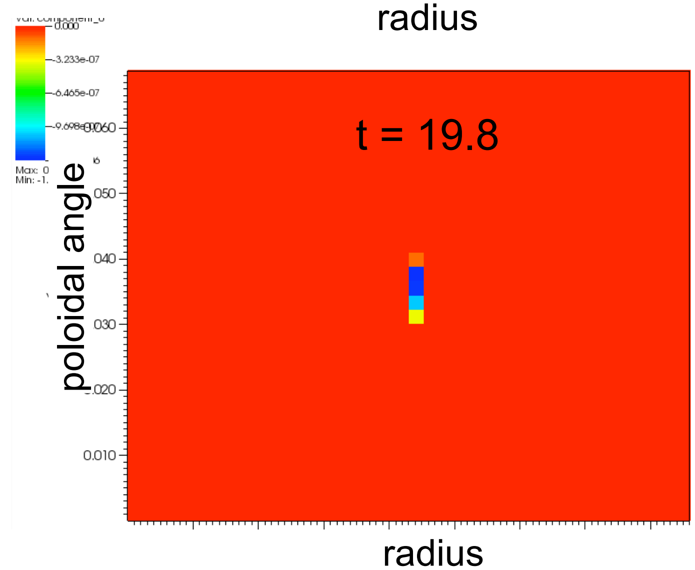
1.0

0.094

regions of negative f
(none at t=0,30.6)

(Same $v_{||}$, μ as preceding slide)





Present capability is limited but growing

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- Now: just beginning.
  - GK equation
  - Non-circular core geometry (Miller) plus toroidal limiter
  - Field solve is long-wavelength limit of GK-Poisson (not yet run together with GK equation -- next on the test list)
  - Limited creature comforts; visualize results via VISIT-readable HDF5 files that include geometry mapping
  - Explicit (4th order) predictor-corrector
  - Parallel in all dimensions ("born parallel")
- In progress
  - A source class that will enable explicit volumetric sources and a Krook collision operator
  - Activate additional moments
  - Extension to 5D partly in place
  - Multiblock grid capability for divertor geometry simulations
- Many things remain on to-do list
  - Gyro averaging, collision model upgrade, implicit time advance, neutral gas transport, EM, AMR, more user features, …
  - More collaborators welcome!
    - Project meeting at LBL May 20-21.