SIMULATING EXTREME ANISOTROPY WITHOUT MESH ALIGNMENT

Carl Sovinec
Univ. of Wisconsin-Madison

Tom Gianakon
Los Alamos National Laboratory

MHD Working Group, Oct. 28 2001
APS 2001, Long Beach CA

- Nonlinear simulations of high-temperature plasmas must be able to resolve thermal transport anisotropy associated with the magnetic field direction.
  - The saturation of pressure-driven modes is sensitive to changes in magnetic topology due to parallel thermal conduction.
  - The ratio of parallel to perpendicular thermal conductivities leads to one threshold mechanism for neoclassical tearing modes.
- When the magnetic field is aligned with the grid or when the angle between $\hat{\mathbf{b}}$ and the grid is uniform, the anisotropy is accurately represented by standard techniques.
- A nonlinearly evolving magnetic topology requires more sophisticated approaches:
  - There is curvature in the magnetic field.
  - The topology of islands and stochastic regions is three-dimensional.
  - Even 3D automated mesh refinement schemes would be severely challenged by these conditions; 3D refinement is possible but 3D alignment near a separatrix is not.
- The **NIMROD** code has addressed this challenge by using high-order finite-element basis functions, which represent curvature with or without alignment.
  - The increase in spatial convergence rates with basis function order has been verified.
  - Spatial convergence rates are retained with nonuniform meshing.

A quantitative measure of the numerical error can be determined by a simple test problem.

- The simplest thermal conduction problem is a 2D box with Dirichlet boundary conditions and a source. If the source drives the lowest eigenfunction only,

  $$S(x,y) = 2\pi^2 \cos(\pi x)\cos(\pi y)$$

  in the domain

  $$-0.5 \le x \le 0.5, -0.5 \le y \le 0.5 \;,$$

  it produces the temperature distribution

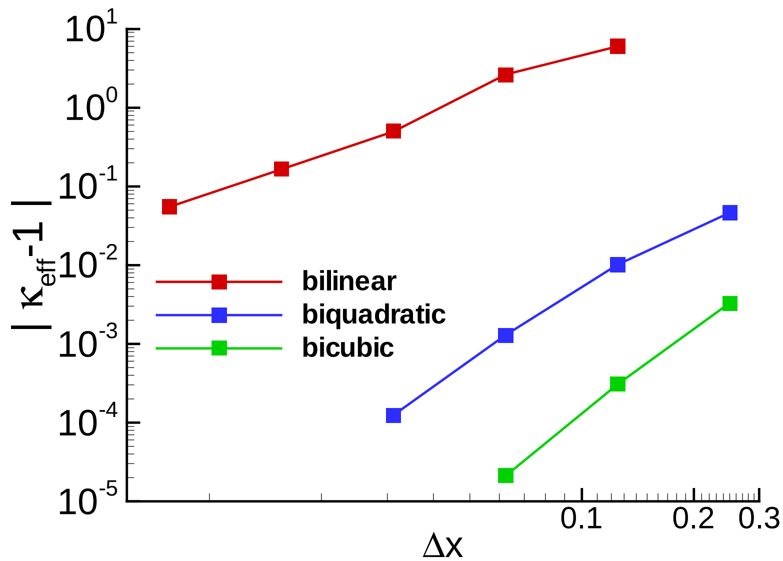
  $$T(x,y) = \kappa^{-1} \cos(\pi x)\cos(\pi y) \;.$$

- A numerical test with $\boldsymbol{B}$ everywhere tangent to this temperature distribution and a uniform rectilinear grid has $\hat{\mathbf{b}}$ severely misaligned with the grid. With $\kappa_\perp = 1$ and $\kappa_\| >> 1$, the inverse of the resulting $T(0,0)$ is a good measure of the effective $\kappa_\perp$ of the numerical algorithm.

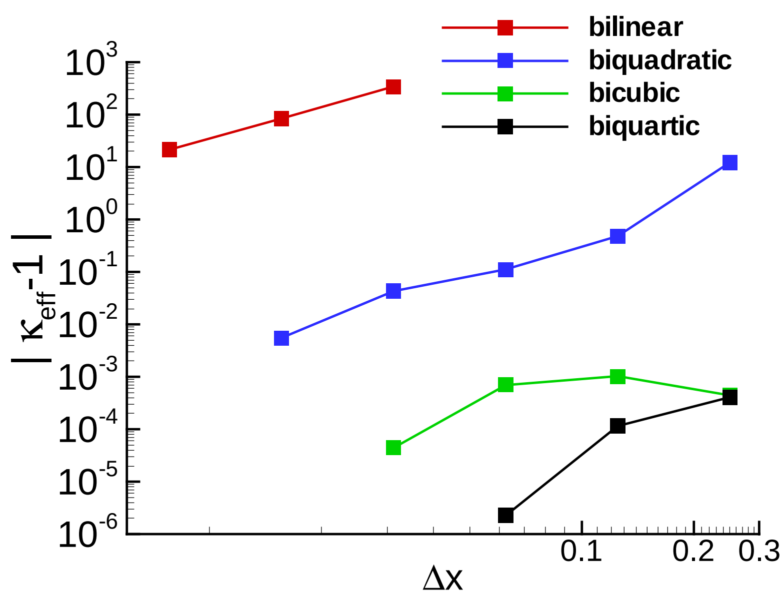
- The magnetic field is created by inducing a perpendicular current density distribution that is proportional to the heat source.

Results from the Anisotropic Diffusion Test

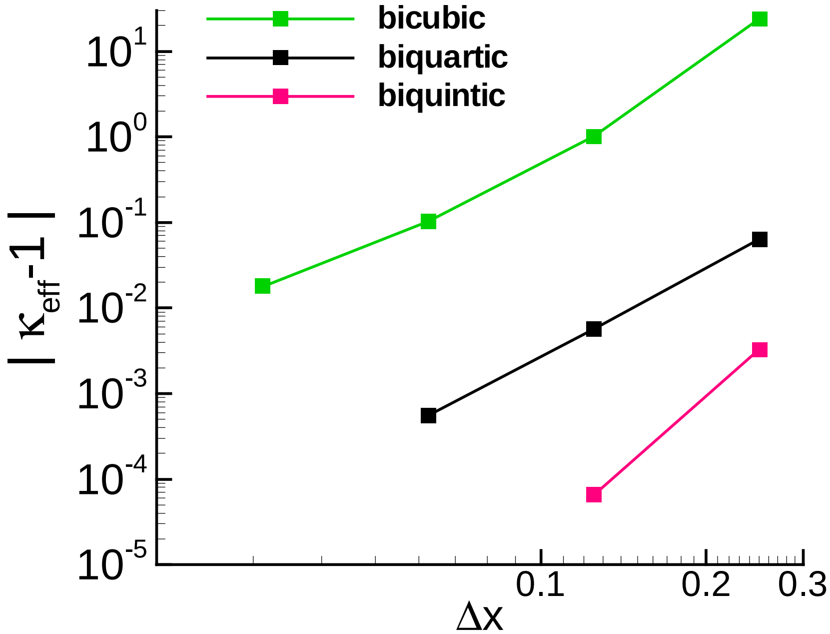
Effective κ_{perp}-1 for $\kappa_{||} = 10^3$



Effective κ_{perp}-1 for $\kappa_{||} = 10^6$



Effective κ_{perp}-1 for $\kappa_{||} = 10^9$



High-order basis functions enable resolution of extreme anisotropy in nonlinear simulations of electromagnetic fusion physics.

Finite elements also provide geometric flexibility.

These NIMROD features are making a wide range of tokamak and alternates simulations possible.

Anisotropic Diffusion Demonstration

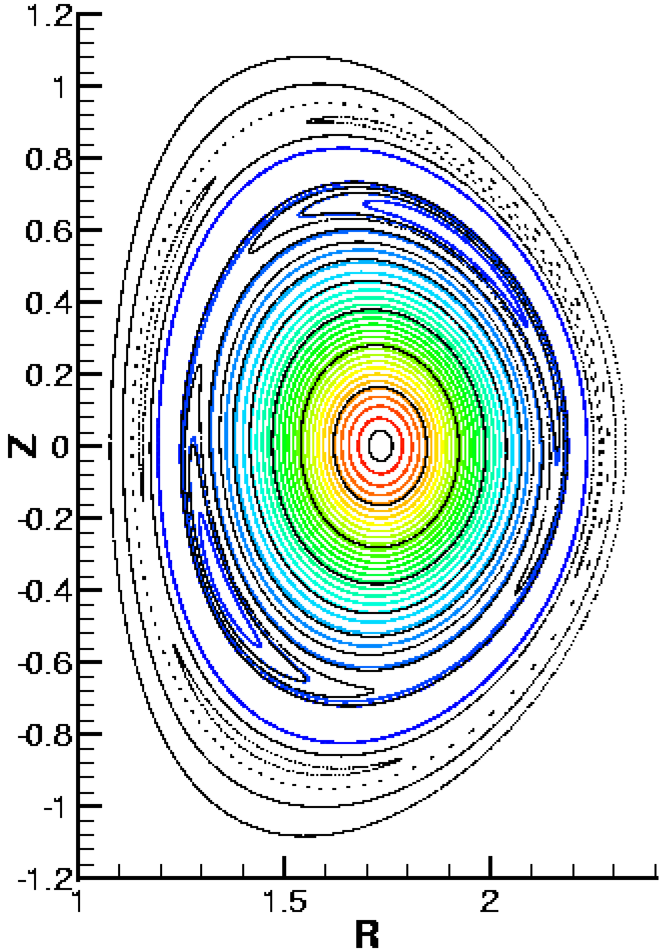
- Start from S=10^4, P_m=0.1 saturation of Test Problem 1b (DIII-D-like equilibrium) that had κ_{iso}=0.423 m^2/s=0.1ν.

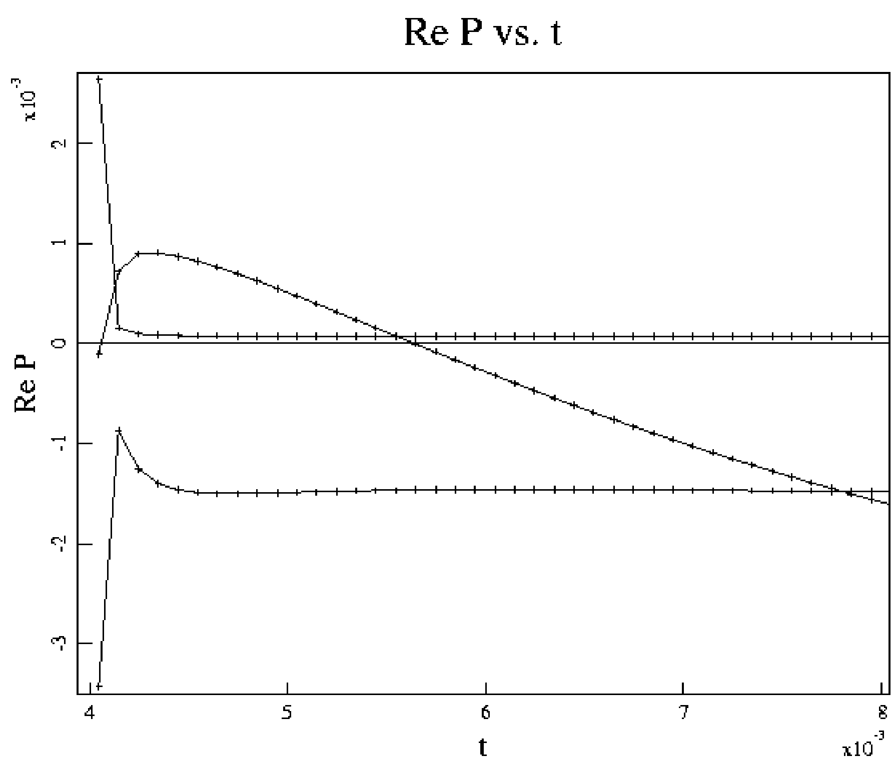
- Freeze magnetic evolution and just run anisotropic thermal diffusion over the perpendicular time-scale (100 x resistive time-scale).

- $\kappa_\perp$=0.423, $\kappa_\parallel$=4.23x10^8, Δt=1x10^{-4} s.

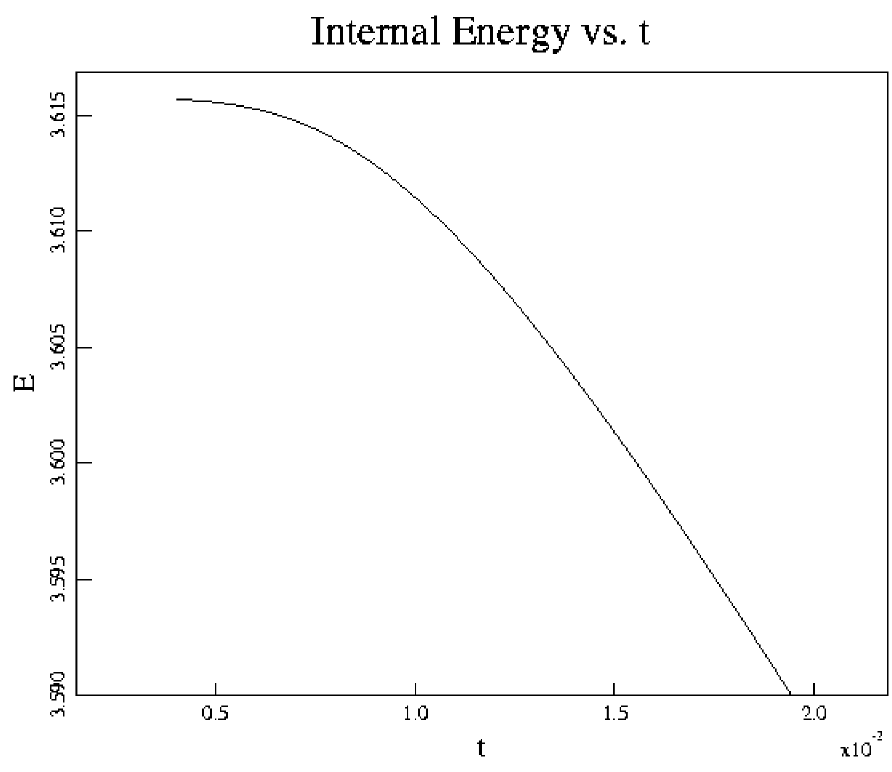
- Island appears in pressure contours immediately.

Pressure contours (color) after 1.5 ms of anisotropic diffusion overlaid with Poincare surface of section.





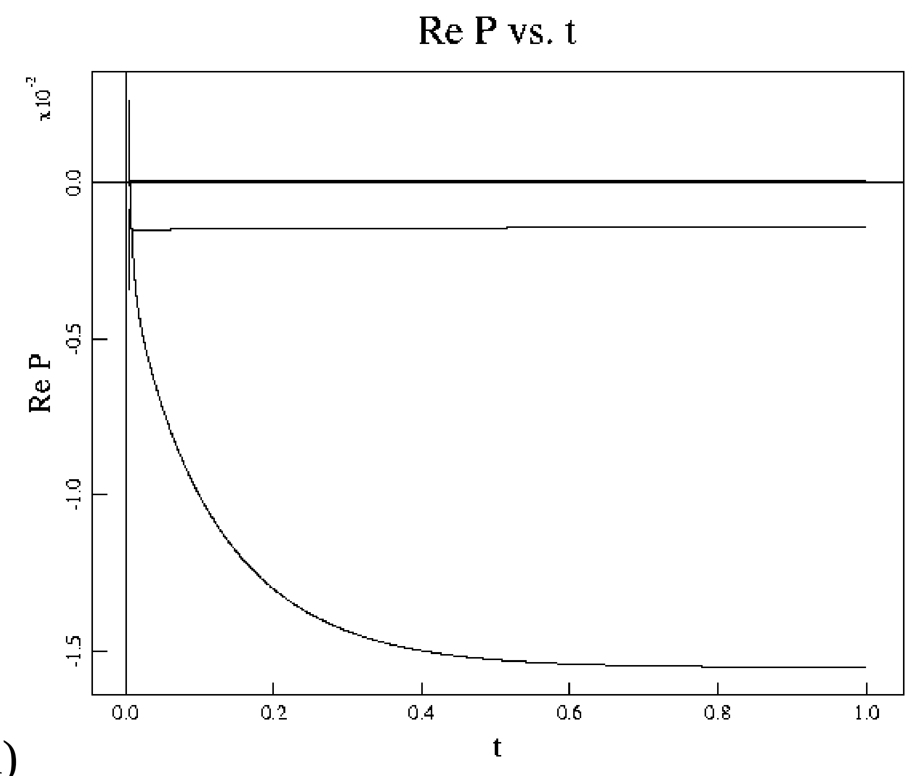
a)



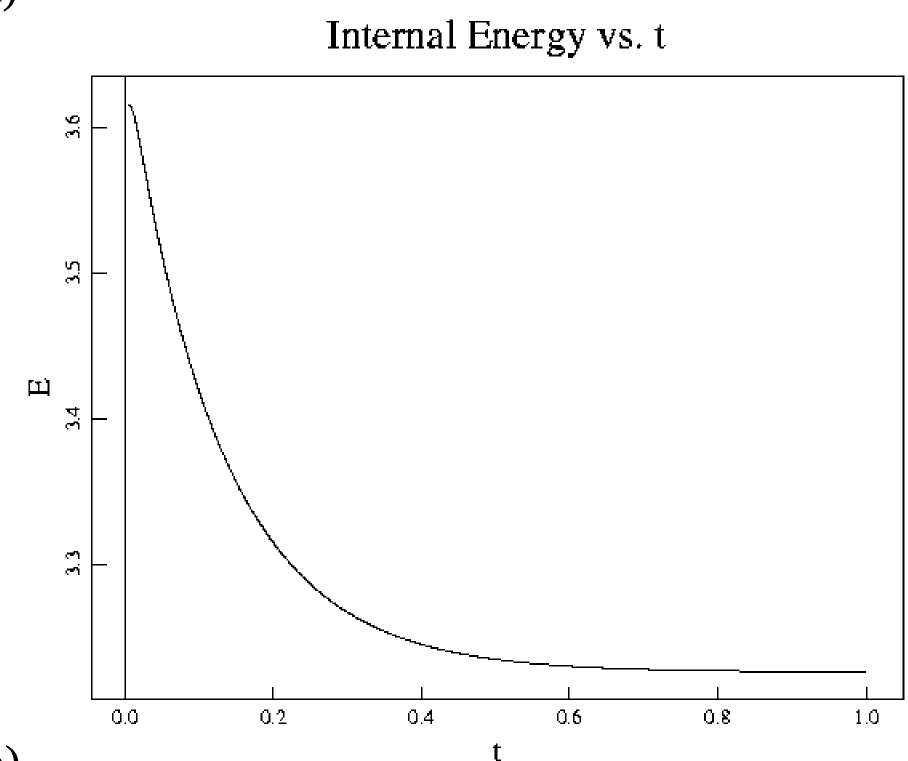
b)

a) "Probe" located at (R=1.312, Z=-0.248) and b) internal energy vs. time. Time-scale in a) is ms, and in b) it's 10 ms.

- Steady-state transport is regained after a perpendicular diffusion time.



a)



b)

a) "Probe" and b) internal energy. Time-scale is seconds.

- The n=0 pressure profile inside the island drops over the long time-scale, reflecting the loss of insulation over the magnetic island.