WS, llc

Extended MHD Simulations of the Compression of Compact Tori Using NIMROD

Angus I. D. Macnab

Woodruff Scientific, LLC

WS, 11c

Outline

- NIMROD Background
  - Benefits of NIMROD
  - Comparison to other codes
- Recent Simulation Results
  - 2-fluid Effects
  - Translation and Flux Compression
  - Liner compression
- NIMROD Development Path for CT Compression
  - Supersonic capabilities
  - Atomic physics
  - Boundary conditions
- Conclusion

WS, 11c

NIMROD is a Robust 3D Nonlinear Extended MHD Code[2]

- High order finite elements in 2D with a finite Fourier expansion in 1D.
- Semi-Implicit operator with implicit advection and diffusion.
- Anisotropic transport.
- Robust Hall MHD Implementation.

[2]C.R. Sovinec et al., J. Comp. Phys. **195**, 355 (2004)

WS, 11c

NIMROD Equation Set

Continuity

$$\frac{\partial n}{\partial t} + \nabla \cdot \left(n\mathbf{u} \right) = 0$$

Momentum

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \mathbf{J} \times \mathbf{B} - \nabla \mathbf{P} + \nabla \cdot \overleftrightarrow{\Pi}$$

Temperature

$$\frac{n_s}{\gamma - 1} \left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) T_s = -P_s \nabla \cdot \mathbf{u}_s - \Pi_s : \nabla \cdot \mathbf{u}_s - \nabla q_s + Q_s$$

Faraday's Law

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

Generalized Ohm's Law

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} + \eta \mathbf{J} + \frac{1}{ne} \left(\mathbf{J} \times \mathbf{B} - \nabla \mathbf{P}_\mathbf{e} \right)$$

WS, 11c

NIMROD is Appropriate for Compact Tori Modeling

- 2-Fluid effects through Hall and electron pressure gradient terms.
- FLR effects through nonlinear gyroviscosity.
- Hot particle effects through hybrid particle closures.
- Complicated 3D geometries through mapping from logical to physical.
- Well validated and verified.

WS, 11c

NIMROD Compares Favorably with Other Codes

	NIMROD	HyM	Mach3	Moqui	LB-MHD
Grid	HOFE	FD	FV	FD	FD
3D	1D Fourier	3D FD	3D FV	2D	3D FD
Refinement	Static	No	Adaptive	Lagrangian	Static
Hall	Robust	Yes	Yes	No	No
Supersonic	Diffusive Mach 0-2	No	Yes	Yes	No
FLR	Gyrovisc	Particles	No	No	No
Hot Particles	Particles	Particles	No	No	No
V&V	Large Use	Several Users	Large Use	Legacy	Needs Work
Parallel	1-1000 PE	Unknown	1-1000 PE	1 PE	Petascale

WS, 11c

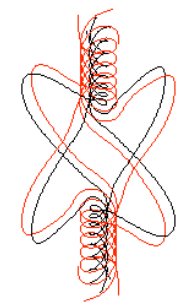
Outline

- NIMROD Background
  - Benefits of NIMROD
  - Comparison to other codes
- Recent Simulation Results
  - 2-fluid Effects
  - Translation and Flux Compression
  - Liner compression
- NIMROD Development Path for CT Compression
  - Supersonic capabilities
  - Atomic physics
  - Boundary conditions
- Conclusion

WS, 11c

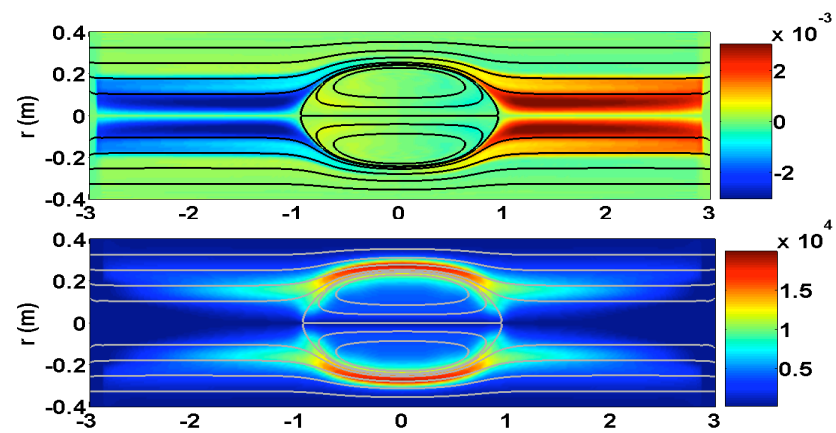
FRC Rotation Depends on Hall MHD[1]

- Plasma quickly rotates at ion diamagnetic frequency, often causing rotational instabilities.
- Rotation due to end-shorting is modeled.
- Spin-up occurs even for resistive boundaries.



$$\mathbf{v}_\perp = \frac{\mathbf{E}\times\mathbf{B}}{B^2} + \frac{1}{ne}\left(\mathbf{J}_\perp - \frac{\mathbf{B}\times\nabla P_e}{B^2}\right) + \frac{\mathbf{B}\times\eta\mathbf{J}}{B^2}$$

$$v_\theta = \frac{1}{ne}\left(J_\theta - \frac{B_z\partial_r P_e}{B^2}\right)$$



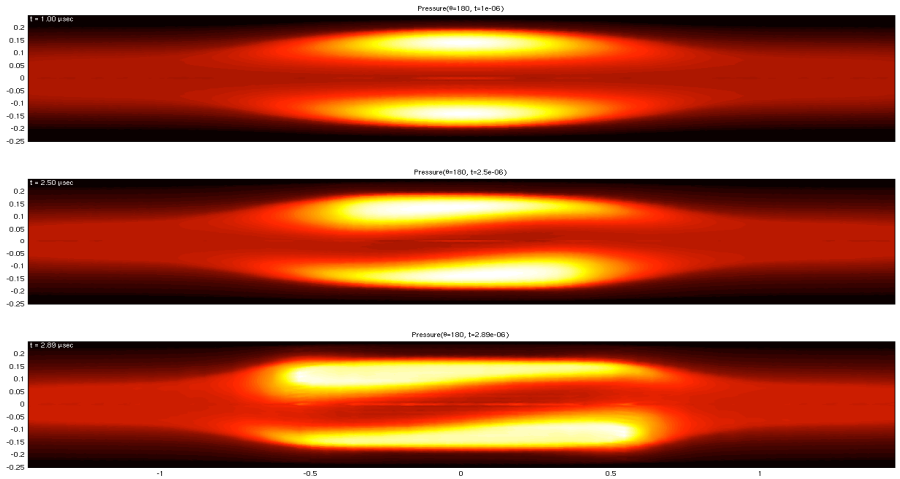
[1]Macnab et. all POP **14** 092503 (2007)

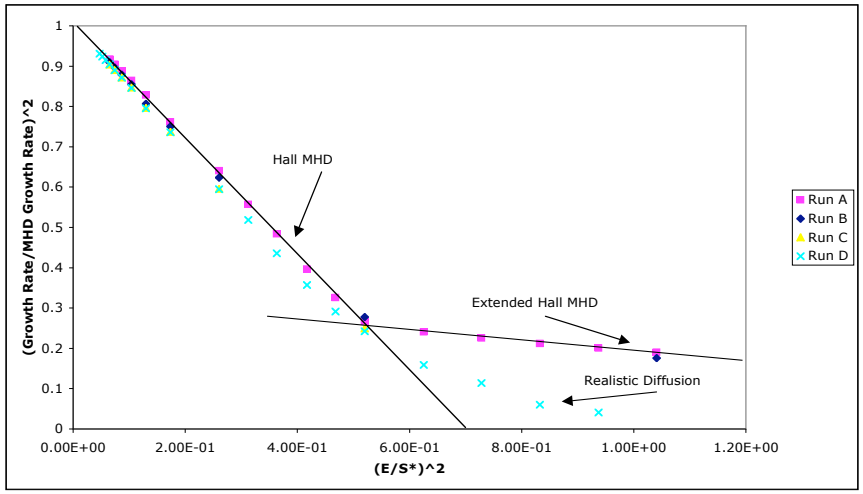
WS, 11c

The FRC Tilt Mode is Slowed by Hall MHD

- Actual growth times are longer than predictions of resistive MHD.
- HMHD effects slow the mode's growth.
- Is not easily verified by experiment.
- FLR and hot particle effects will further slow the growth rate (e.g confirming Belova et al.)

$$\gamma^2 = \gamma_{MHD}^2 \left[1 - \left(\frac{a}{S^* / E} \right) \right]$$

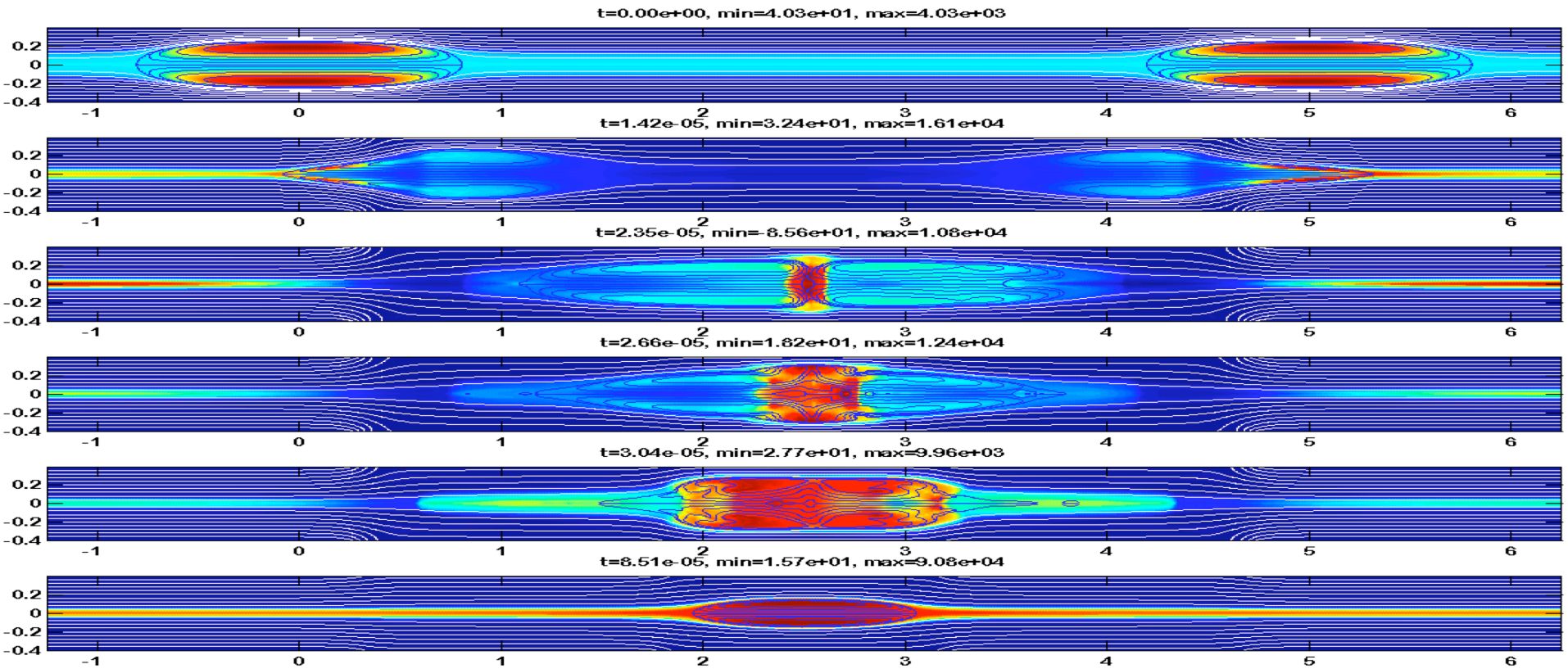




WS, llc

CT Compression and Merging Rates are Affected by Hall MHD

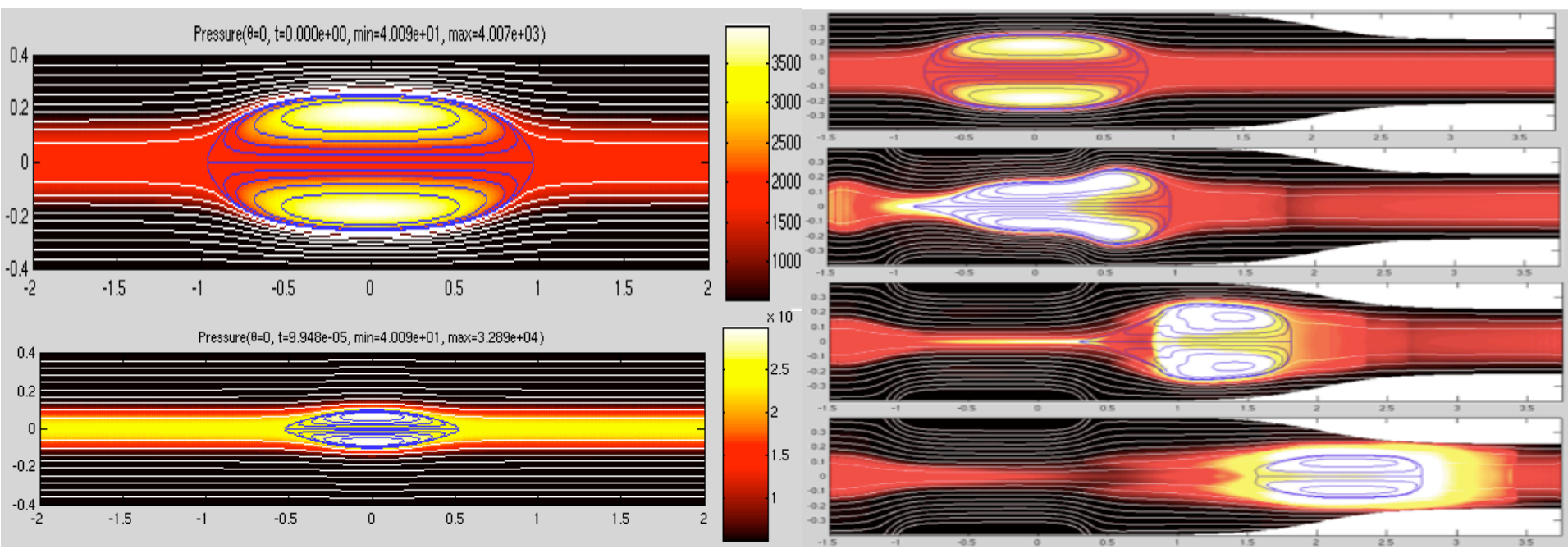
- Supersonic theta-pinch translation is recovered.
- FRC collisions generate (diffusive) shocks.



WS, 11c

Flux Compression

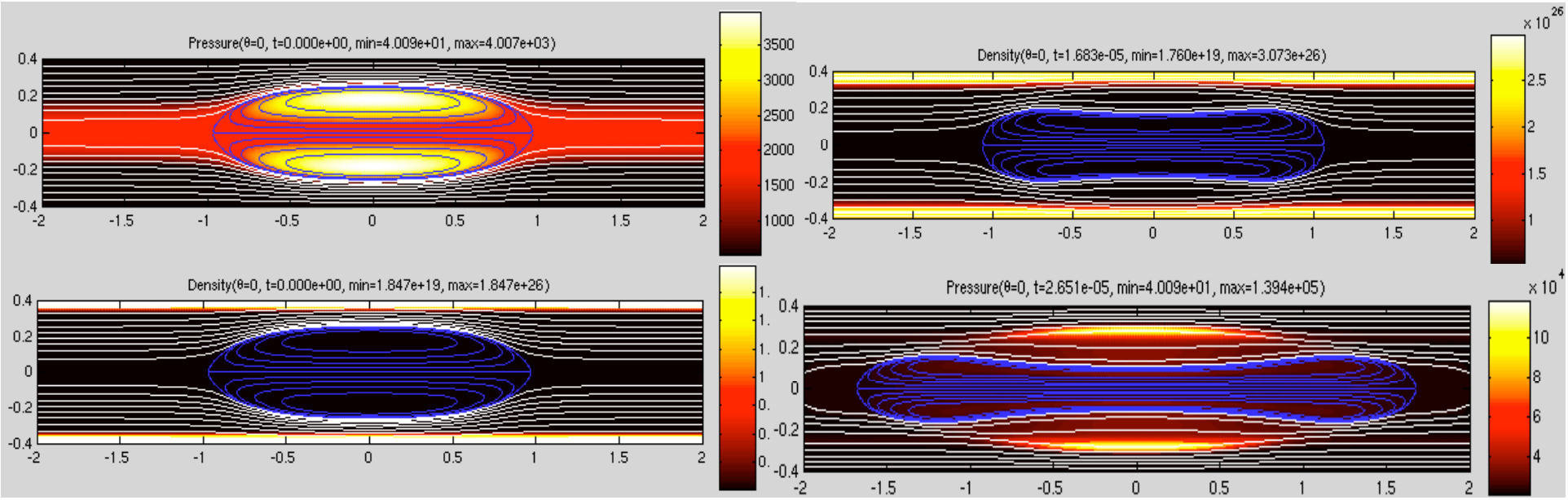
- Theta-Pinch Coils can be used to compress a CT radially and axially through various schemes.
- Pressure contours with magnetic flux lines are shown



WS, llc

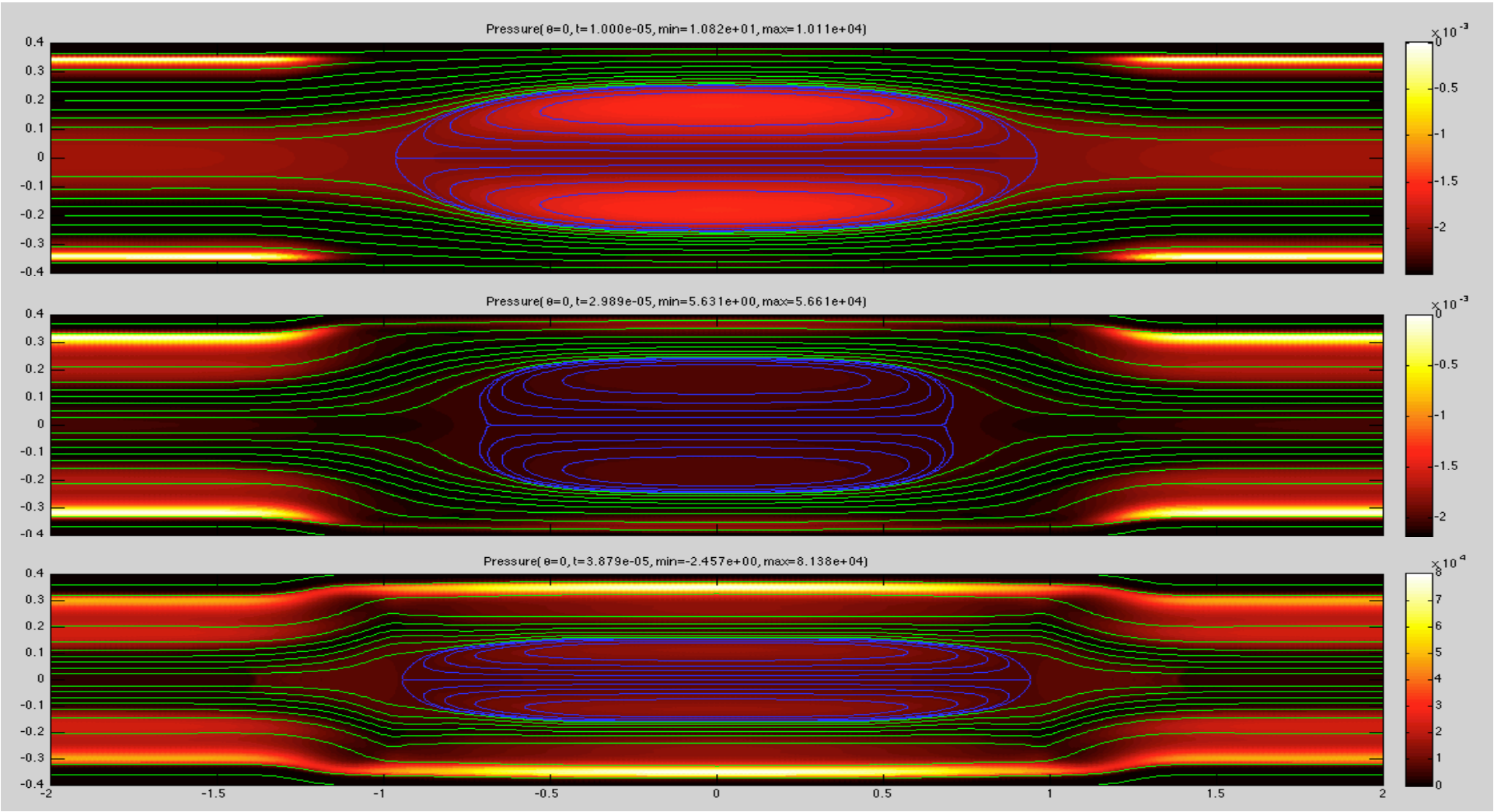
Liner Compression Studies Indicate Need for Coil Shaping

- The mass density increases by a large factor near the radial wall to mimic a liquid liner.
- Pressure, ion temperature and number density contours with magnetic flux superimposed.



WS, llc

Coil Shaping Increases Axial Compression



WS, 11c

Outline

- NIMROD Background
  - Benefits of NIMROD
  - Comparison to other codes
- Recent Simulation Results
  - 2-fluid Effects
  - Translation and Flux Compression
  - Liner compression
- NIMROD Development Path for CT Compression
  - Supersonic capabilities
  - Atomic physics
  - Boundary conditions
- Conclusion

WS, 11c

Shock Capturing Capability will Enable NIMROD for MTF

- Supersonic translation only currently works with diffusive shocks.
- Discontinuous Galerkin or Pettrov-Galerkin methods for non-oscillatory shock capturing.
- Fairly involved low level programming of a new NIMROD kernel.

WS, 11c

Atomic Physics Effects are Important to CT Compression

- Atomic physics packages are in limited use in NIMROD
- Separate species evolution for mixing
- Liquid and plasma liners and plasma jets
- Effects of neutrals near the walls

WS, 11c

Metal Liner Compressions Require Moving Boundaries

- Improves compression efficiency
- Possible within the R(ix,iy), Z(ix,iy) NIMROD framework
- Careful attention to mass, momentum and energy transfer from the wall

WS, llc

Conclusions

- Woodruff Scientific, LLC possesses a unique capability for modeling the dynamics of CT formation, translation, and compression.
- Liquid liner and flux compression scenarios are actively being addressed.
- Effects of Hall physics, FLR and hot particles can be modeled in a robust manner using NIMROD.
- Future development will include shock capturing capabilities, atomic physics, and moving boundaries.