NIMROD Simulations of Reconnection in MRX and SSX

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Motivation

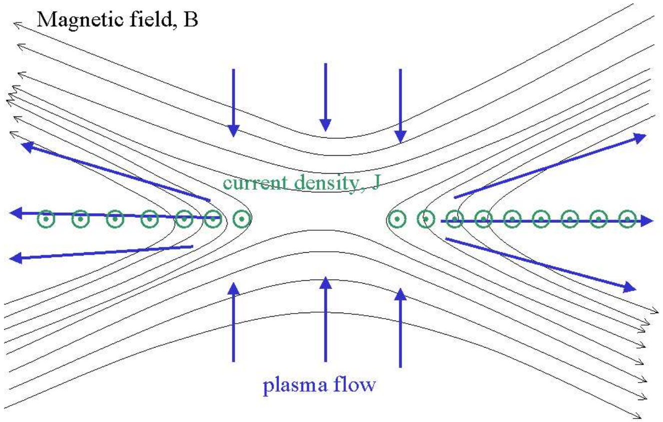
- Most studies of reconnection focus on local reconnection physics
- The reconnection layer can communicate with the global magnetic field via dispersive waves
- The global magnetic field topology can in turn affect the reconnection rate
- We will study the relationship between local reconnection physics and global magnetic field evolution by simulating the Swarthmore Spheromak Experiment (SSX) and the Magnetic Reconnection Experiment (MRX)

Outline

- Introduction to reconnection physics
- Creating MRX's nontrivial finite element grid
- First nonlinear simulations of push and pull reconnection in MRX
- Preliminary simulations of spheromak merging in SSX
- Discussion of possible neutron star accretion project

Introduction to Magnetic Reconnection

- Magnetic reconnection is the breaking of the frozen-in condition on length scales much less than the global length scale
- Oppositely directed field lines are pushed together
- A thin diffusive layer allows field lines to break and reconnect
- Reconnection is observed in the magnetosphere, solar flares, and lab experiments



Issues in Reconnection

- Is there a causal relationship between fast reconnection and adding a Hall term in the Generalized Ohm's Law?

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} + \eta \mathbf{J} + \frac{1}{ne}\mathbf{J} \times \mathbf{B} + \frac{1}{ne}\nabla \cdot \underline{\mathbf{p}}_e$$

- How does the diffusive layer communicate with the global magnetic field configuration?
- Is it the local physics or the global magnetic field arrangement that determines the reconnection rate?
- Does the magnetic topology rearrange itself so that reconnection occurs at the rate at which it is driven?

Non-Ideal Hall MHD Model

NIMROD solves the equations of extended MHD cast in a single fluid form. The relations between E, Π, and $\mathbf{q}_\alpha$ determine which model is solved.

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left(\eta \mathbf{J} - \mathbf{V} \times \mathbf{B} + \frac{1}{ne} \mathbf{J} \times \mathbf{B} - \frac{1}{ne} \nabla p_e \right)$$

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

$$\nabla \cdot \mathbf{B} = 0$$

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

$$\frac{\partial n}{\partial t} + \nabla \cdot (n \mathbf{V}) = \nabla \cdot D \nabla n$$

$$\frac{n}{\gamma - 1} \left(\frac{\partial T_\alpha}{\partial t} + \mathbf{V}_\alpha \cdot \nabla T_\alpha \right) = -p_\alpha \nabla \cdot \mathbf{V}_\alpha - \nabla \cdot \mathbf{q}_\alpha + Q_\alpha$$

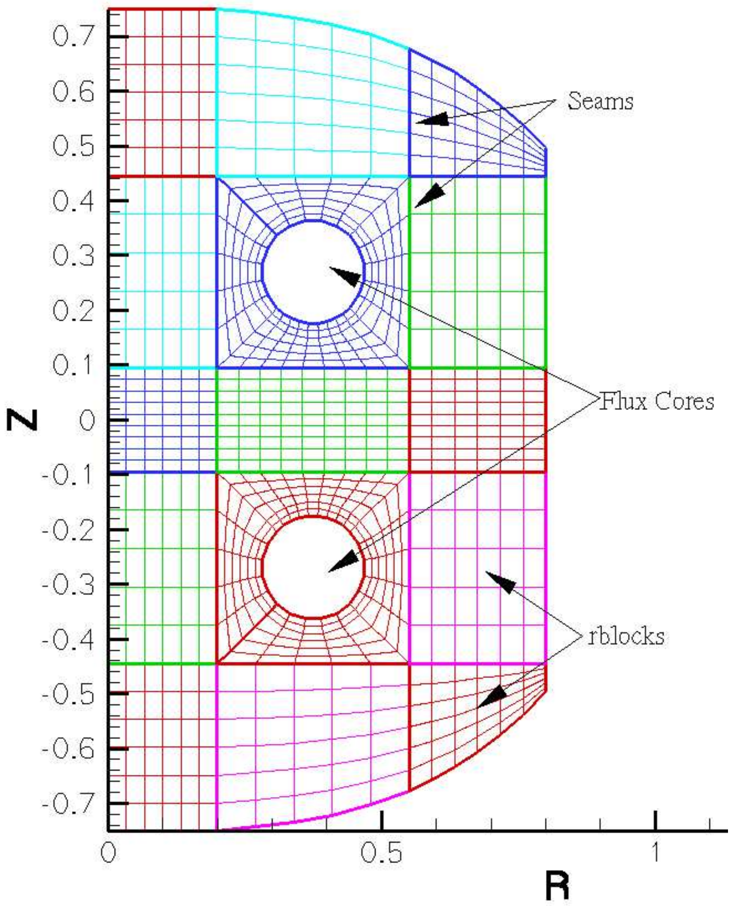
Previous simulations of MRX and SSX

- MRX
  - Watanabe et al. (1998) model magnetic island formation
  - Lukin & Jardin (2003) use TRIM for resistive MHD and include a “model Hall” term to approximate two-fluid effects
- SSX
  - Lukin et al. (2001) perform TRIM simulations of partial spheromak merging
  - E. Belova has done related work on spheromak merging and FRC stability

Setting Up MRX's Finite Element Grid

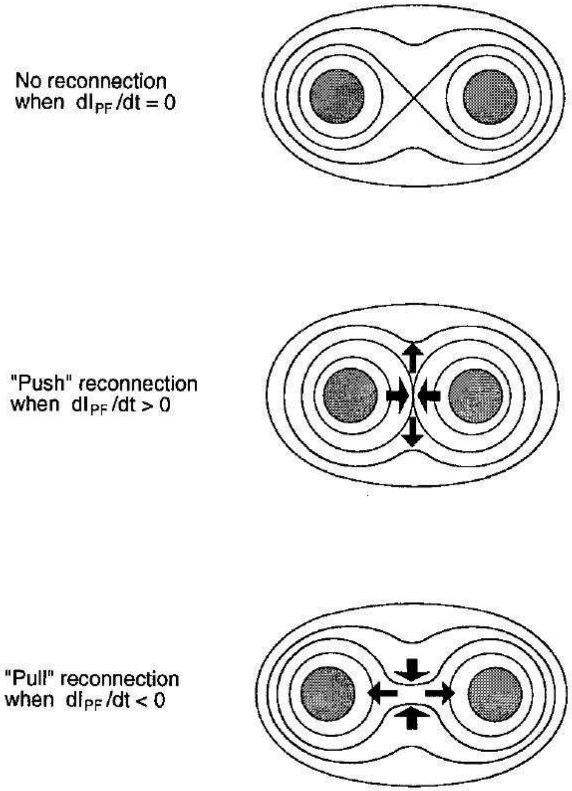
- The grid for MRX is nontrivial due to the presence of dual flux cores. Much of NIMROD's preprocessing and postprocessing assume that the gridshape is *logically rectangular*. It is necessary to depart from this assumption and use a logically nonrectangular grid.
  - Position data is stored in 15 separate logically rectangular 'rblocks'
  - Connectivity between gridblocks must be manually programmed into seam data structures
  - Flux core positions can be varied
  - Circular current loops provide vacuum magnetic fields
  - Poloidal and toroidal electric fields can be applied on flux core surfaces

MRX's Finite Element Grid



- MRX has a nontrivial geometry which requires significant modification of NIMROD's preprocessing and postprocessing routines.

MRX Modes of Operation



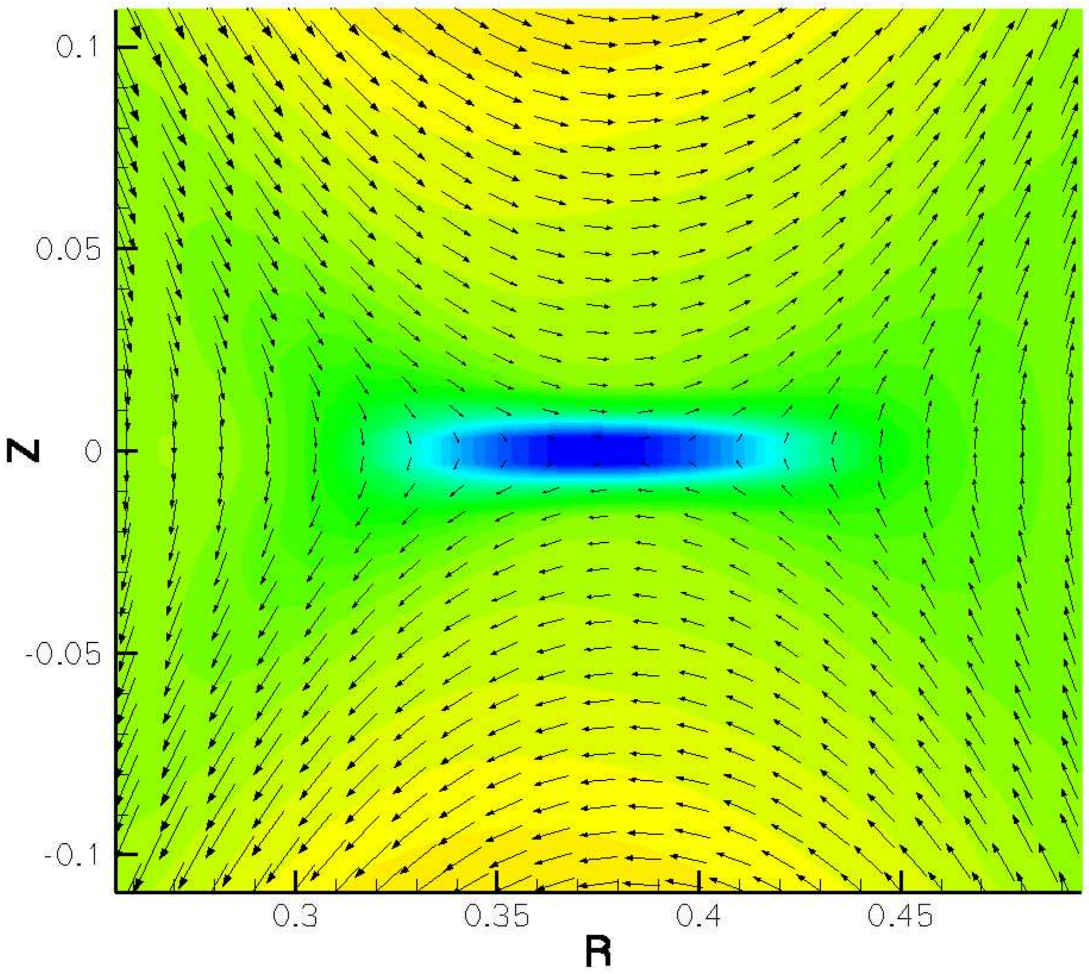
By changing the currents in the flux cores, two distinct modes of reconnection can be induced in MRX. A third mode involving spheromak merging is not shown. (Yamada et al. 1997)

Simulations of MRX

The first resistive MHD simulations of co-helicity push reconnection and null-helicity pull reconnection in MRX show the development of double Y-point current sheets.

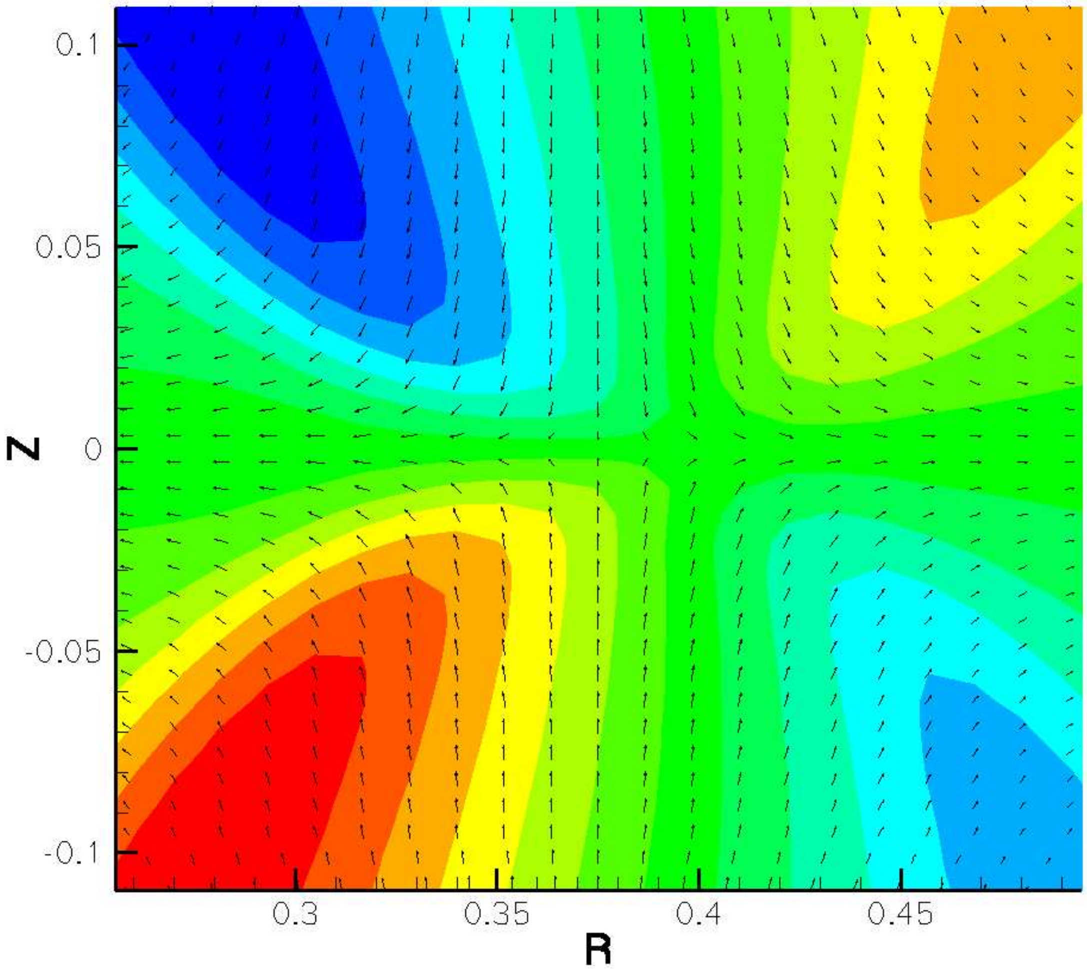
- The initial conditions include a magnetic field resulting from circular current loops in each flux core and two external equilibrium field coils
- The simulations are nonlinear, axisymmetric, with no density or temperature evolution, and bilinear basis functions for $S \sim 800$ and $\beta = 0$
- Toroidal and/or poloidal electric fields are applied on the flux core surfaces to induce reconnection

J_ϕ contours and B_{pol} vectors



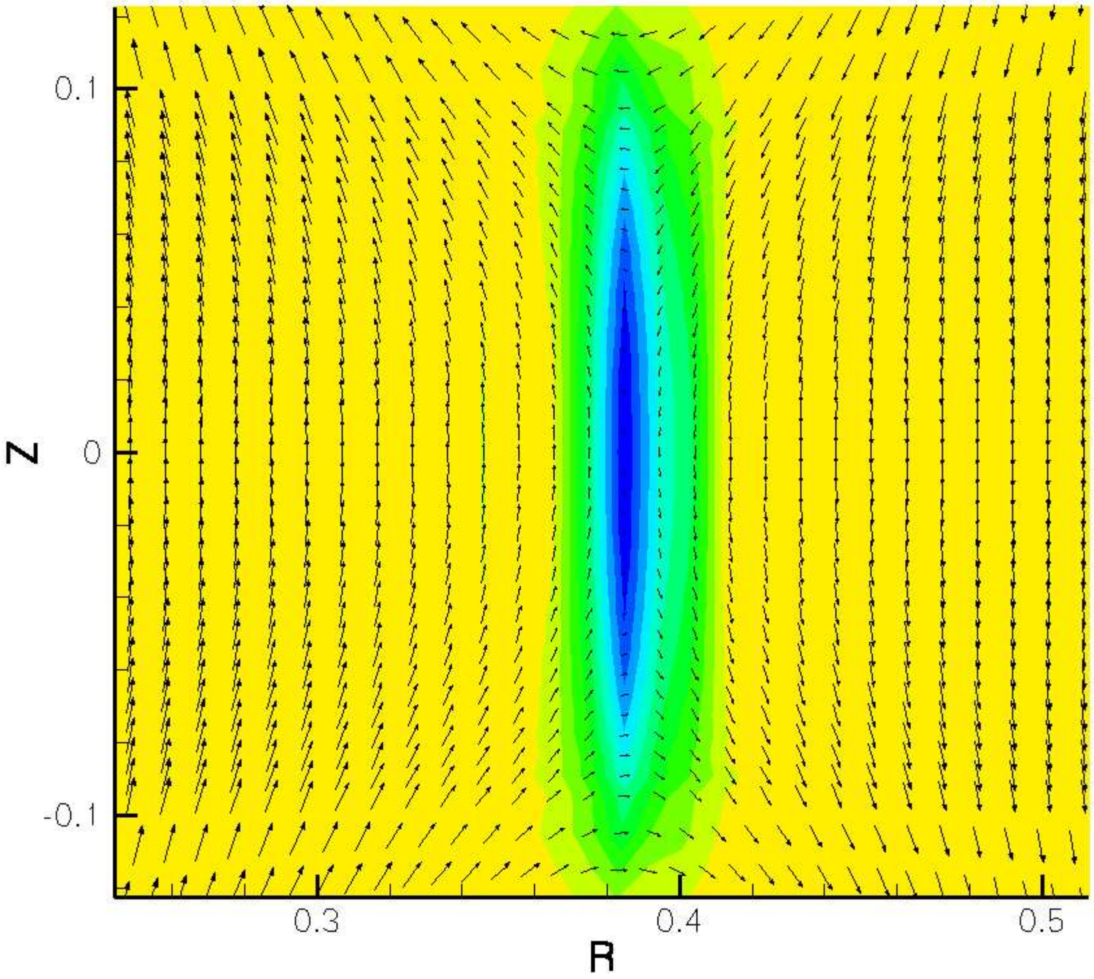
- Co-helicity push reconnection simulations show the development of a current sheet.

V_ϕ **contours and** $\mathbf{V}_{pol}$ **vectors**



- The velocity profiles qualitatively match what is expected for co-helicity push reconnection.

J_ϕ contours and B_{pol} vectors

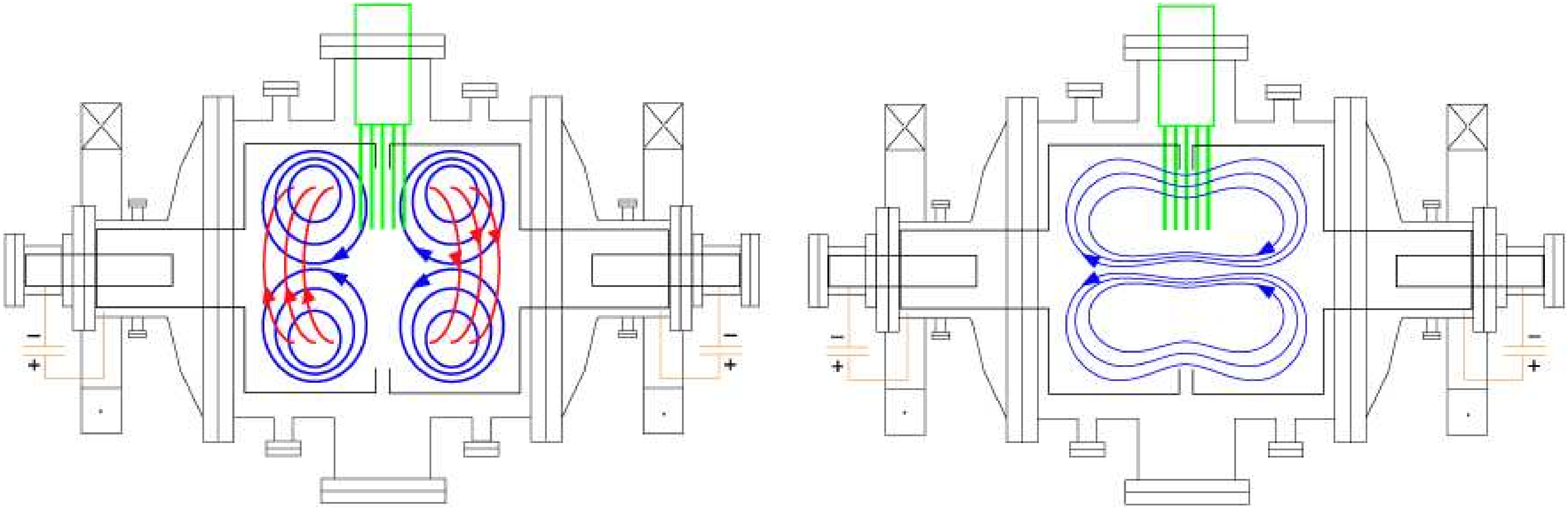


- Null-helicity pull reconnection in MRX shows the development of a double Y-point current sheet.

Future work on MRX simulations

- Further refinement of grid
  - Enable higher order finite element simulations
  - Enhance mesh packing specifically in reconnection region
- Modify postprocessing to allow better visualization from a logically nonrectangular grid
- Directly compare reconnection rates with experiment
- Investigate changing the distance between flux cores
- An axisymmetric two-fluid simulation should be possible soon after the SuperLU library is made compatible with MRX's geometry
  - Look for quadrupole field signature
  - Two-fluid simulation with a guide field

Experimental setup of SSX



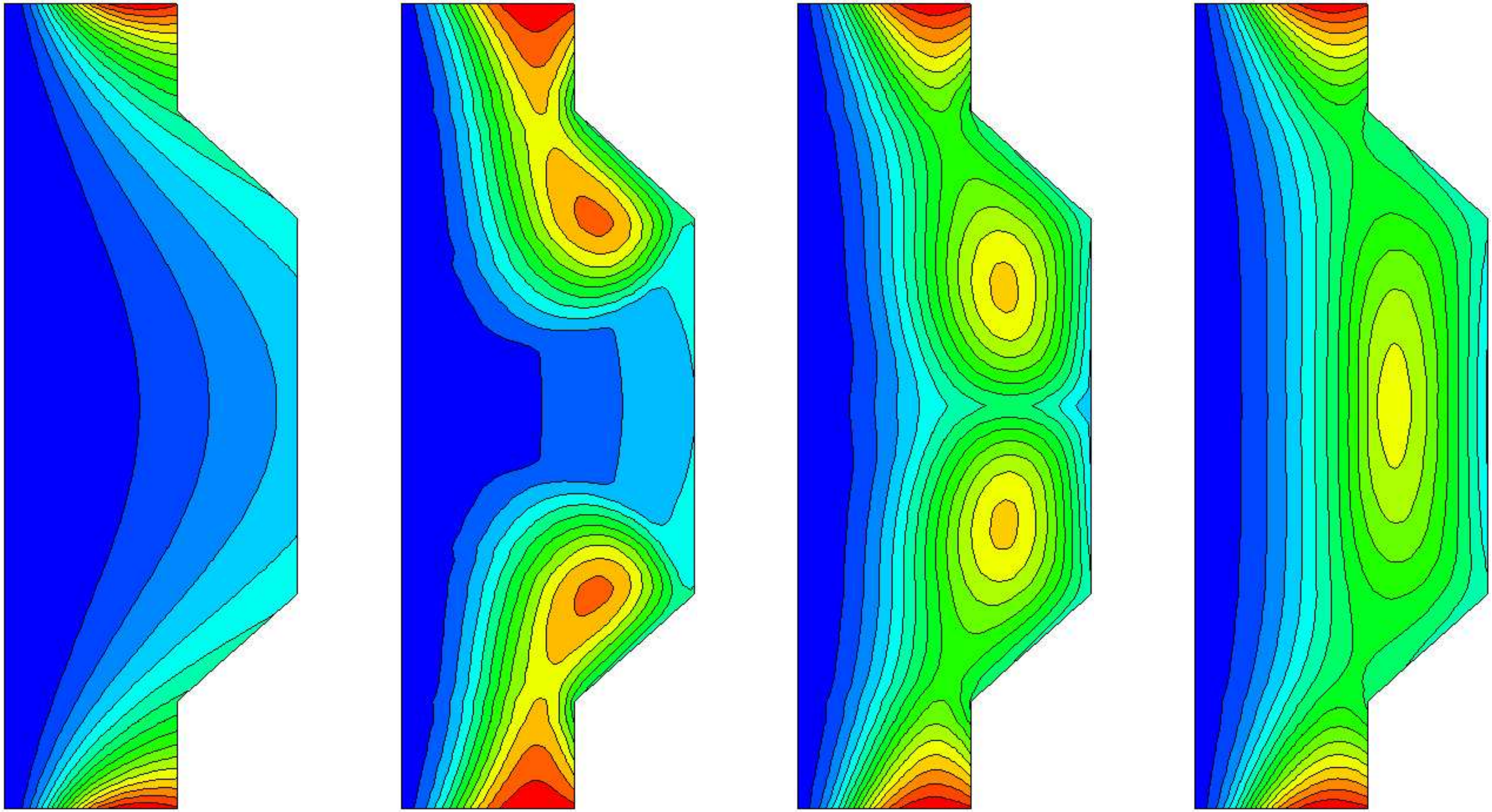
- Two spheromaks are formed by plasma guns
- The spheromaks merge and reconnect at the midplane of the flux conserver
- The resulting Field-Reversed Configuration (FRC) tilts
- This setup is described by Cothran et al. (2003)

Preliminary simulations of SSX

The Swarthmore Spheromak Experiment provides an opportunity to study dynamic magnetic field evolution and reconnection.

- Present resistive MHD simulations use a simplified geometry in a logically rectangular grid
- Radial voltage is applied briefly along the bottom and top surfaces
- The simulation shows partial spheromak formation
- Reconnection occurs at the midplane of the simulation
- We will work towards creating an axisymmetric simulation including Hall effects and a 3-D resistive MHD simulation in a more realistic geometry

Poloidal flux contours in SSX



- Preliminary resistive MHD simulations of SSX show partial spheromak formation and merging.

Future work on SSX

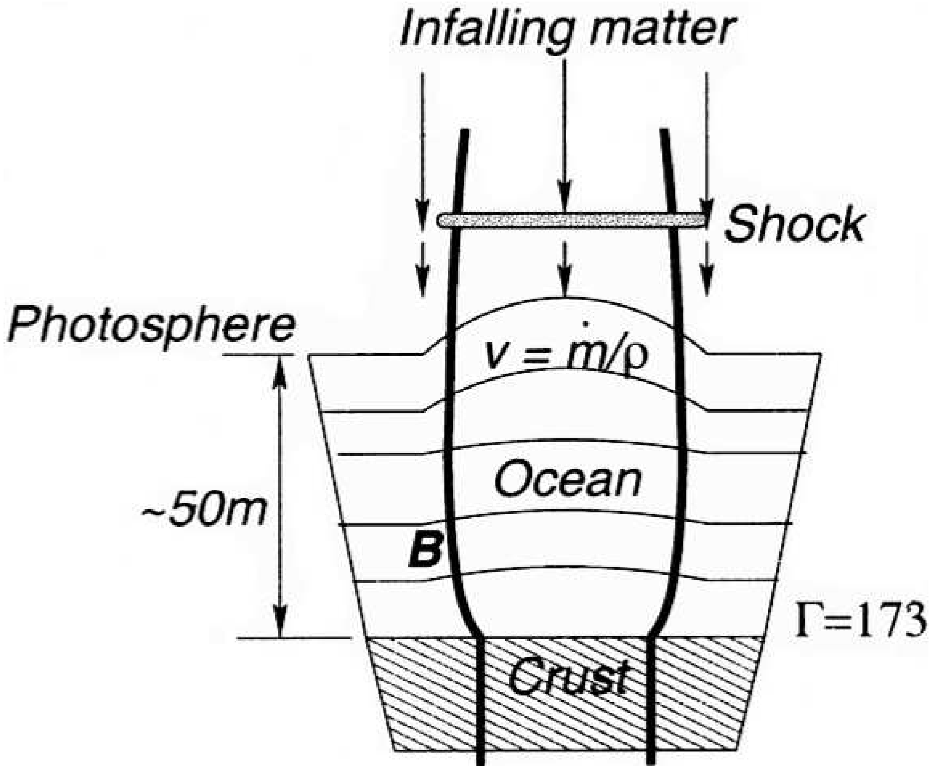
- Design a more realistic geometry
- Match plasma parameters with experiment
- Achieve full flux breakoff from plasma guns
- Perform 2-D two-fluid simulations and 3-D resistive MHD simluations
- Make comparisons to experimental results from magnetic probe arrays and chord-averaged density and velocity measurements

Neutron star accretion project

In addition to simulations of SSX and MRX, the first author's thesis will include an astrophysical application of NIMROD. The most probable project involves following instabilities resulting from polar cap neutron star accretion.

- Material that is accreting onto a neutron star is sucked onto the polar caps
- The resulting material buildup can gradually bury the neutron star's dipole field
- Interchange instabilities and ballooning modes can allow the material to bypass the dipole field
- Litwin, Brown, & Rosner (2001) find regimes where these modes are unstable

Neutron star accretion project



- We will attempt to use NIMROD to follow the evolution of these instabilities near a neutron star surface

Summary

- Resistive MHD simulations of MRX and SSX are underway using NIMROD
    - Nonlinear push and pull reconnection in MRX
    - Partially formed spheromak merging in SSX
- We hope to study the interplay between local reconnection physic and global topology evolution
- A possible future project will follow MHD instabilities in neutron star accretion

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`http://www.astro.wisc.edu/∼murphy/Presentations/APS_2005.pdf`