Global Simulations of Magnetic Reconnection in an Experimental Geometry

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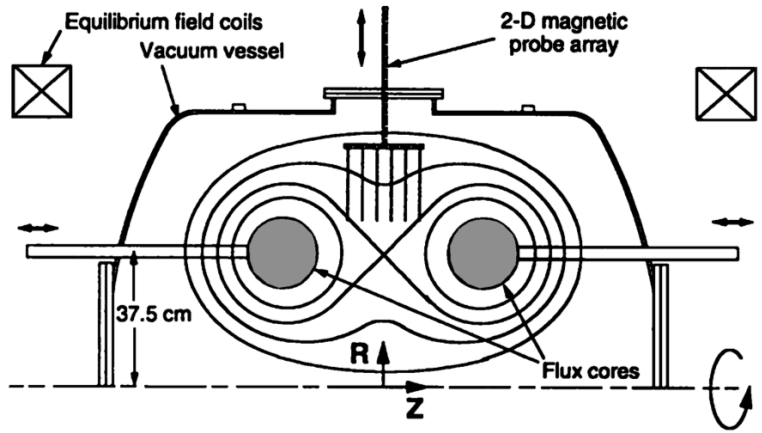
Motivation and Outline

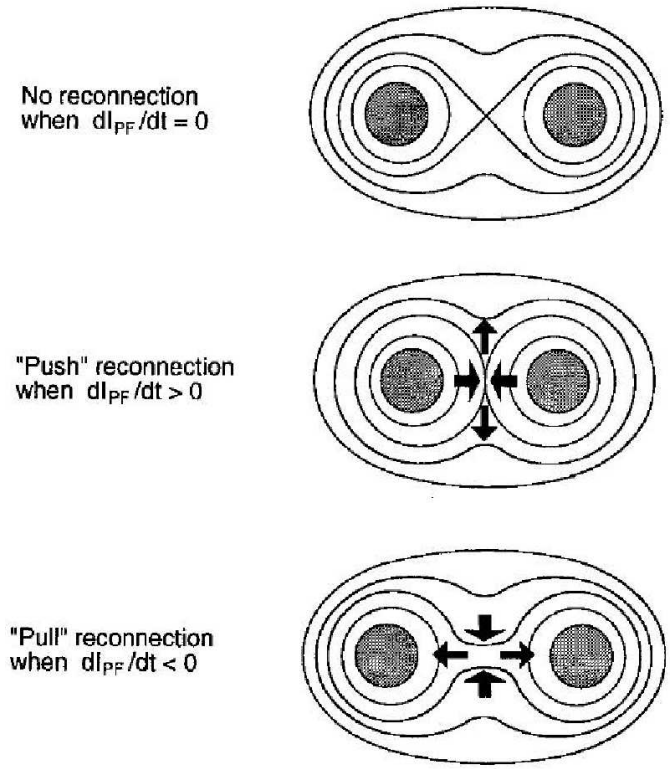
- Most two-fluid studies of reconnection use a simple rectangular domain and Harris sheet equilibrium
- The NIMROD code has the capability to perform two-fluid global simulations in a realistic geometry and examine the impact of large-scale effects on the reconnection process
- In particular, we are interested in how the current sheet feeds back on itself via large pressure gradients
- Outline of talk:
  - Introductions to MRX and the NIMROD code
  - Pressure effects during pull reconnection
  - Asymmetry of the quadrupole field due to toroidicity
  - A comparison of the electron outflow velocity with experiment
  - Pressure effects related to toroidicity during push reconnection
  - Symmetry breaking due to the Hall effect and toroidicity in counter-helicity spheromak merging

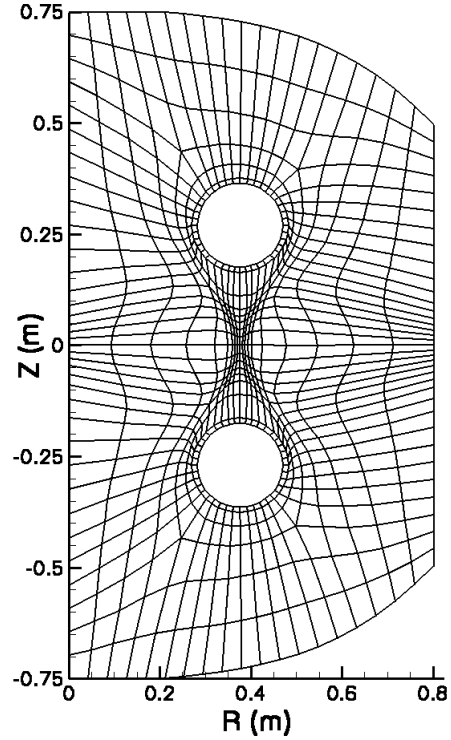
The Magnetic Reconnection Experiment



- The Magnetic Reconnection Experiment (MRX) is located at the Princeton Plasma Physics Laboratory and is designed to study controlled axisymmetric magnetic reconnection
- Plasma parameters: $T \sim 5 - 20$ eV, $B \sim 200 - 500$ G, $S \sim 250 - 2500$, and $n \sim 0.1 - 1 \times 10^{14}$ cm^{-3}
- MRX is a good candidate for computational study because spatial scale separation is moderate and experimental plasma parameters are numerically tractable

MRX Experimental Setup





- *Left:* By changing the currents in the flux cores, two distinct modes of reconnection can be induced in MRX (Yamada et al. 1997). Our NIMROD simulations of MRX investigate both of these modes of operation (Murphy & Sovinec 2008).
- *Right:* A sample finite element grid used for simulations of two-fluid pull reconnection in MRX. The grid is produced with the assistance of a grid smoothing technique. Simulations using a linear geometry contain the flux cores but have a rectangular outer boundary.

NIMROD's Non-Ideal Hall MHD Model

NIMROD solves the equations of extended MHD cast in a single fluid form. The model below is used in simulations of MRX to study the interplay between local and global effects in the reconnection process.

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

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

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

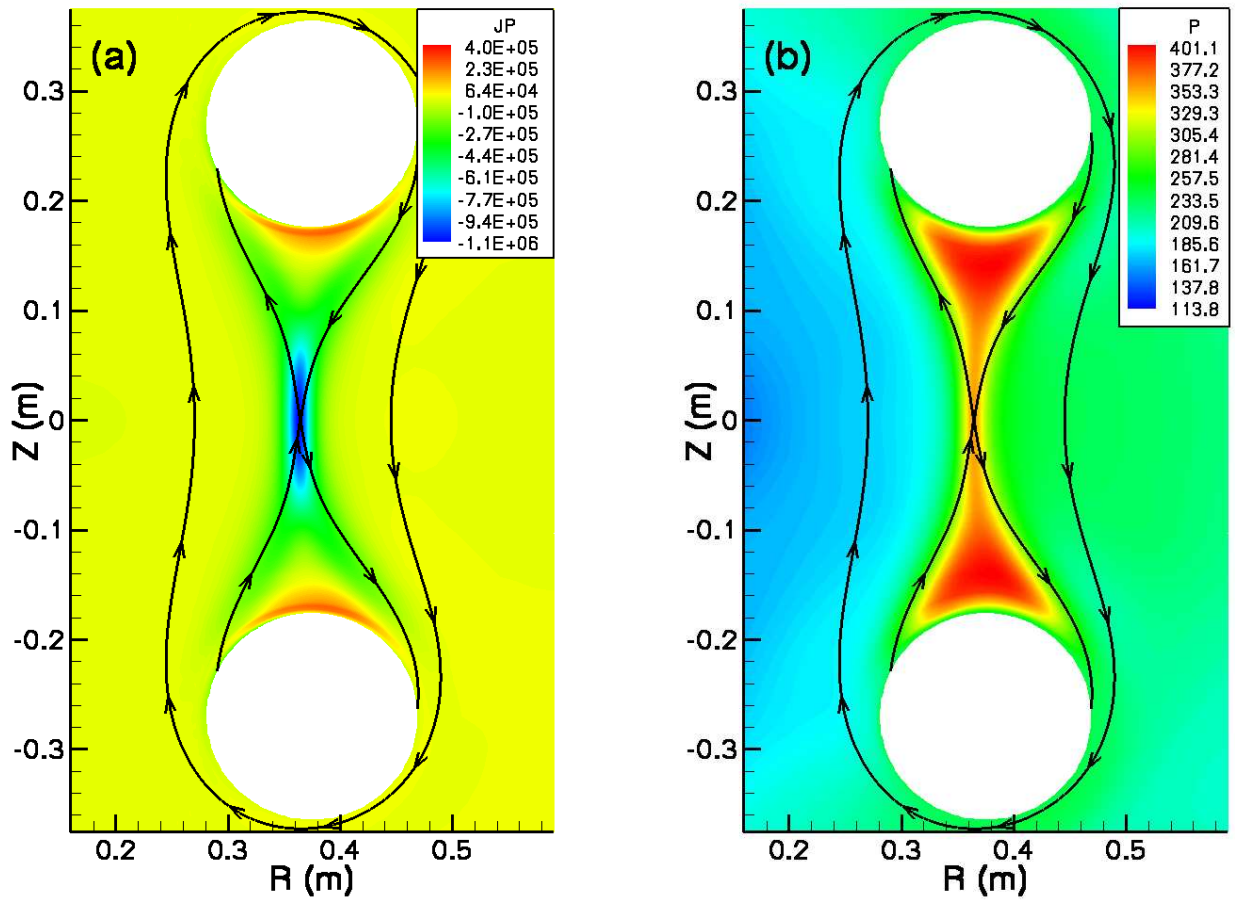
$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \rho \nu \nabla \mathbf{V}$$

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

$$\frac{n}{\gamma - 1} \left(\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T \right) = -\frac{p}{2} \nabla \cdot \mathbf{V} - \nabla \cdot \mathbf{q} + Q$$

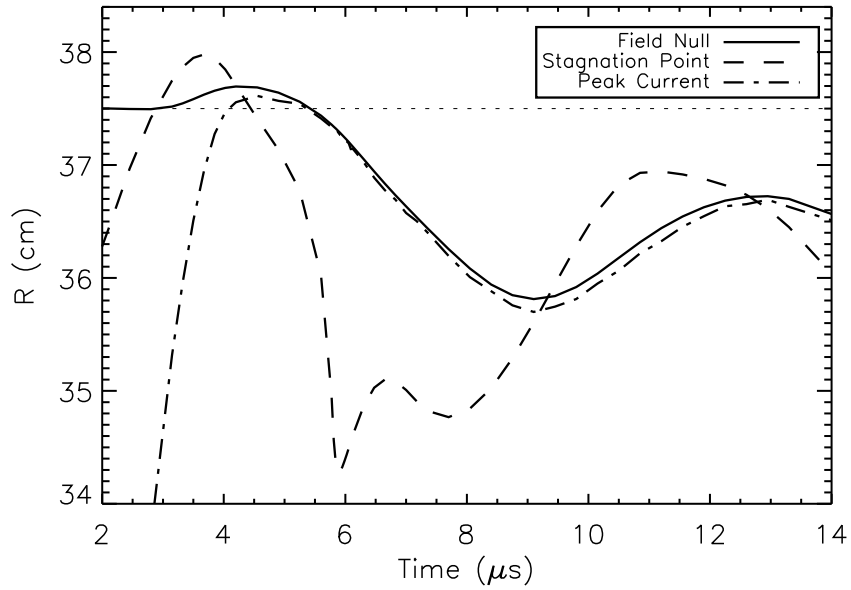
- Two-fluid effects are included via the Hall term and the electron pressure gradient in the generalized Ohm's law (blue). The terms in red are included for numerical purposes.

Simulations of pull reconnection show global pressure effects are important



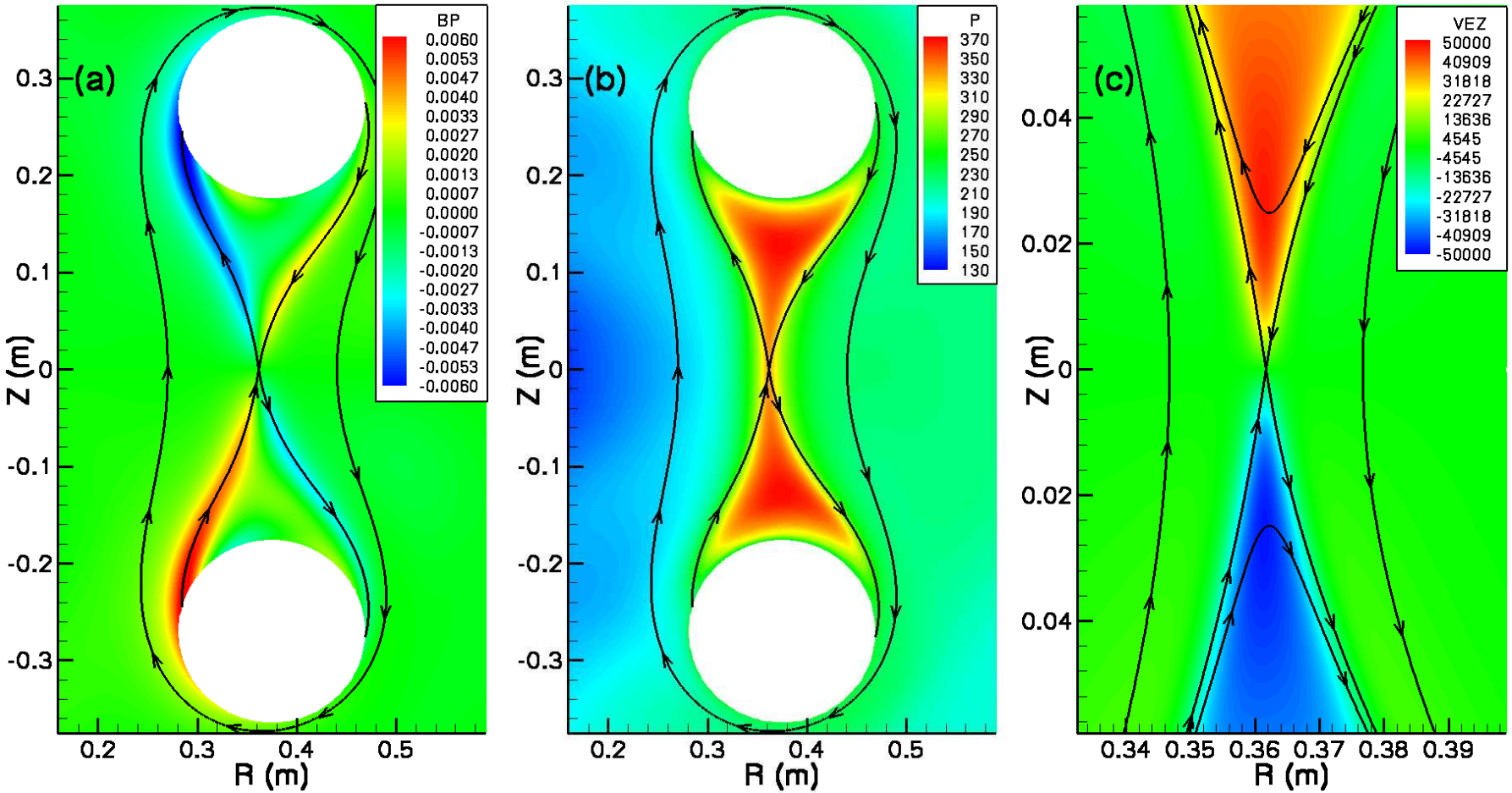
- Toroidal current density contours (left) and plasma pressure contours (right) along with streamtraces of the magnetic field during resistive MHD pull reconnection
- The current sheet length is limited by the flux core separation
- The outflow is greatly slowed due to high downstream pressure
- There is higher pressure on the outboard side of the current sheet than the inboard side

The effects of toroidicity include a radial motion of the current sheet



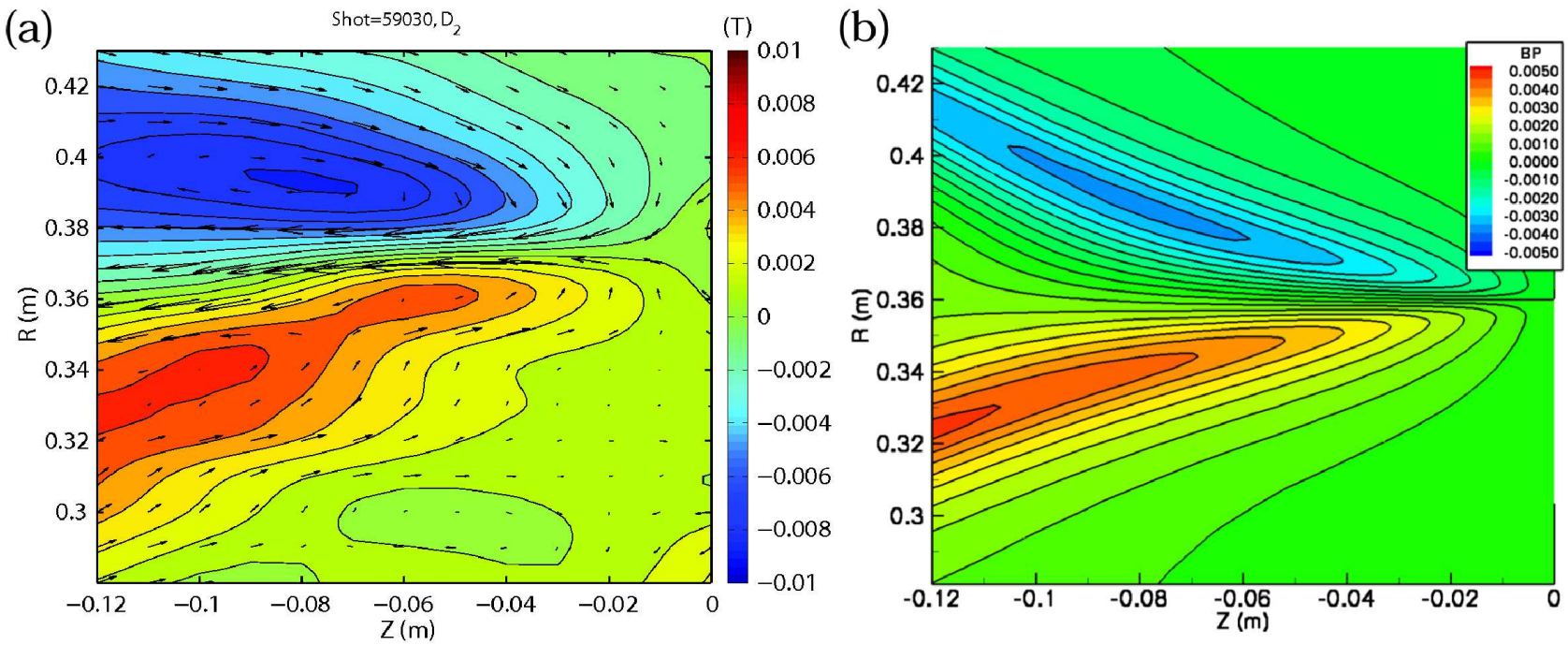
- This radial motion occurs for both resistive MHD (above) and two-fluid models during pull reconnection
- The stagnation point and the field null do not in general coincide
- The drift does not occur if $\beta \equiv 0$ or if linear geometry is used, tying the drift to toroidicity and pressure effects
- The density on the inboard side becomes depleted quickly due to the lesser volume than on the outboard side
- Inflow coming from the inboard side has to undergo a larger jump in pressure than inflow from the outboard side, resulting in a net inward force

The well-known quadrupole is present in two-fluid simulations of MRX



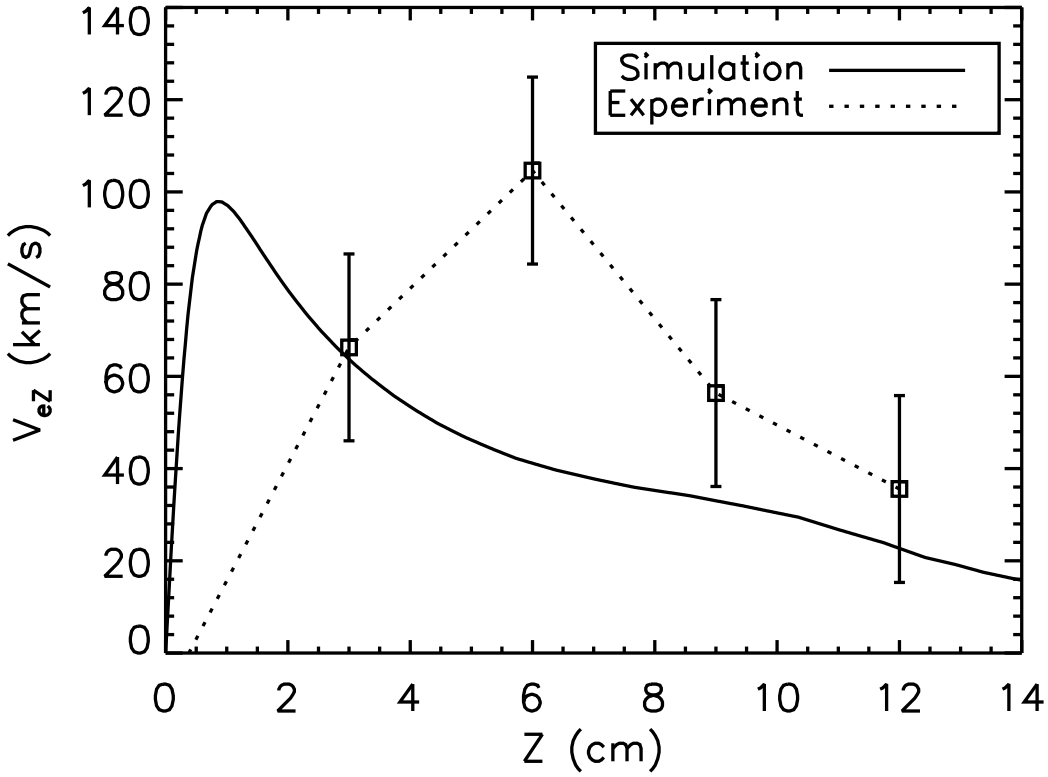
- From left to right are contours of toroidal magnetic field, plasma pressure, and the vertical (outflow) component of electron velocity during the pull mode of reconnection
- The separatrix marks the location of the quadrupole, the strongest pressure gradients, and the boundary between the inflow and outflow regions

The quadrupole shape compares favorably with experiment



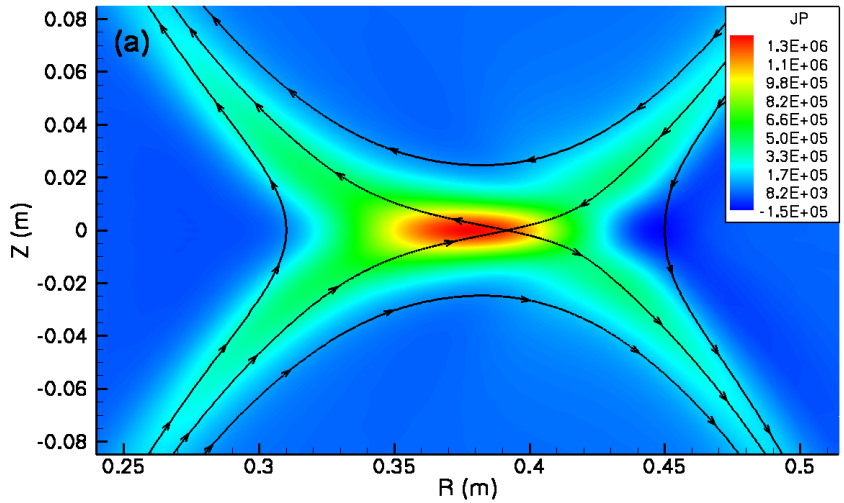
- In both experiment (left) and simulation (right), the outboard quadrupole lobe peaks closer to the X-point than the inboard quadrupole lobe (note the change in orientation of this figure from the previous slide)
- The higher density on the outboard side corresponds to a longer c/ω_{pi} and weaker two-fluid effects
- Here, the asymmetry in density results from toroidicity; see also Pritchett (2008) for fully kinetic simulations of asymmetric reconnection in linear geometry

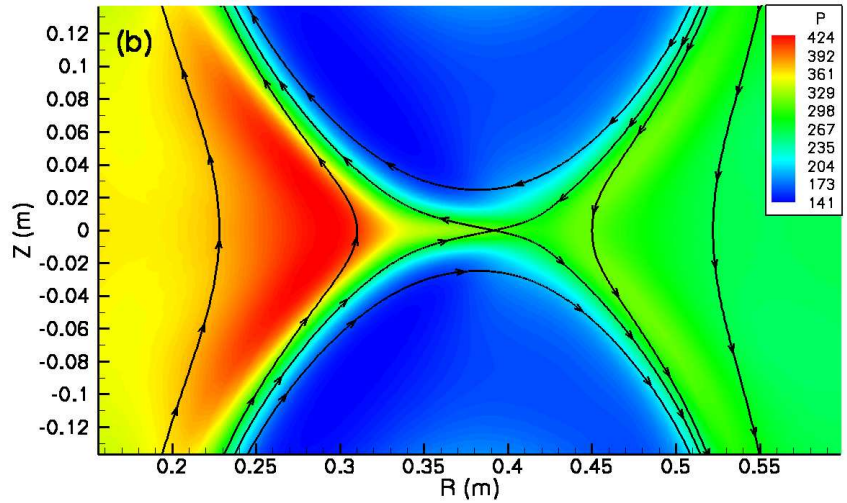
Hall physics alone is not enough to explain the electron outflow velocity profile



- The position of the strongest electron outflow is closer to the X-point in simulation than in experiment, indicative of Hall physics controlling the electron outflow in our simulations
- The elongation of the diffusion region seen in particle simulations (e.g., Daughton et al. 2006) is not seen here
- Recent fully kinetic simulations with geometry similar to MRX allow numerical investigation of electron diffusion layer elongation (see poster by S. Dorfman, this meeting)

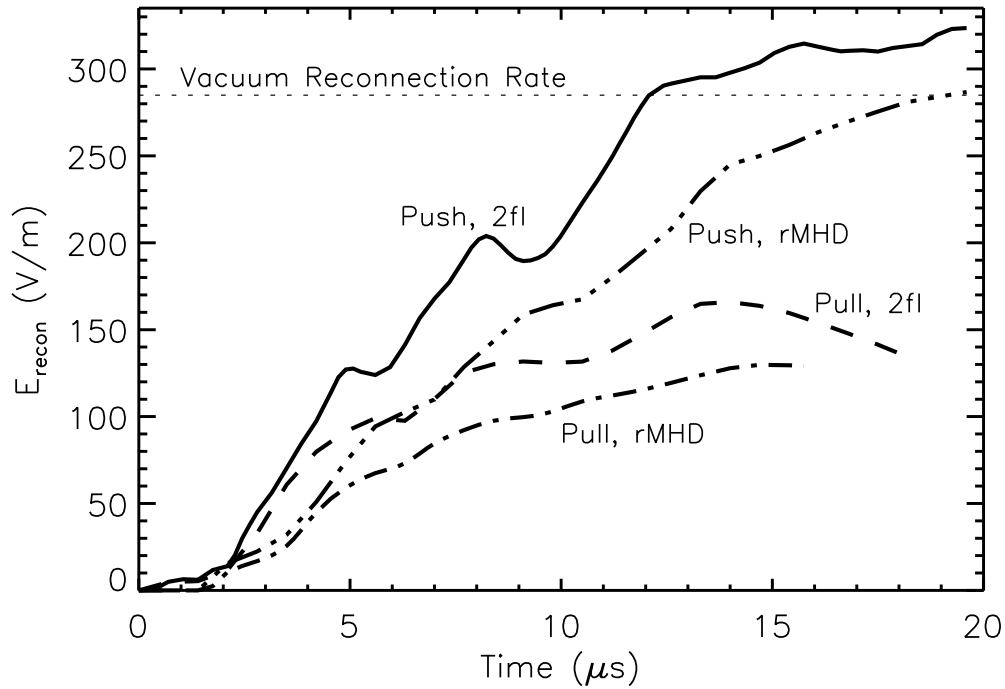
Global pressure differences are also important in push reconnection





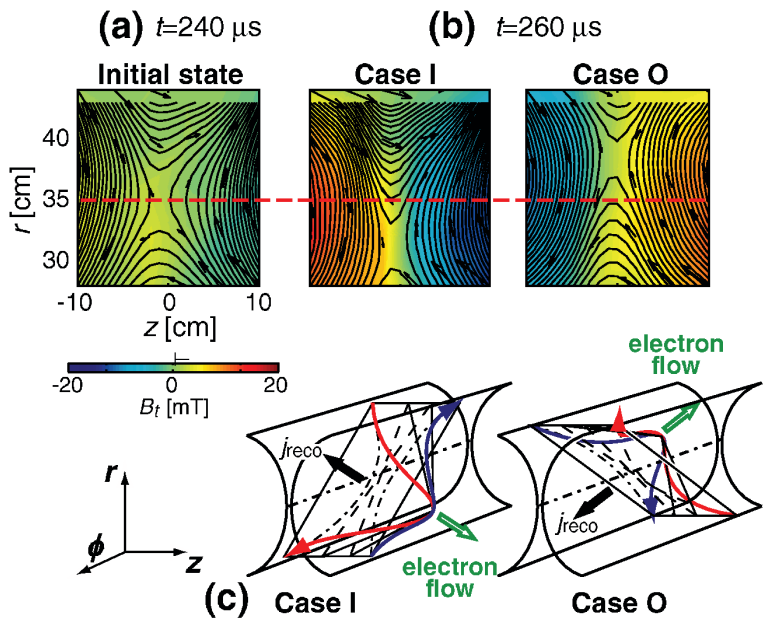
- Due to the same volume effects as in pull reconnection, the inboard downstream region quickly develops high pressure, pushing the X-point to higher radii
- The position of the X-point near the outboard side of the current sheet allows a stronger inward-directed tension force to overcome the steeper pressure gradient
- This is an example of reconnection with asymmetry in the outflow direction (see also my poster, this meeting)

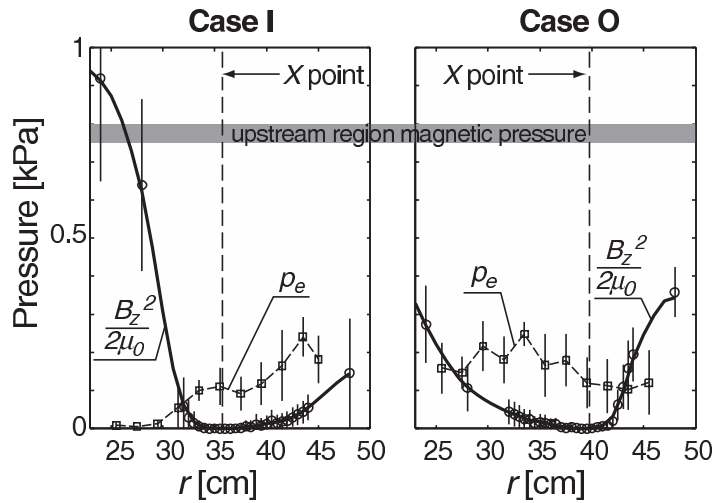
Geometry determines the reconnection rate more than two-fluid effects



- For a given physical model, push reconnection is always quicker than pull reconnection due to the effects of downstream pressure and geometry
- For a given mode of operation, two-fluid reconnection is always quicker than resistive MHD reconnection
- The reconnection rate in this setup depends more on geometric mode of operation than it does on the inclusion of two-fluid effects in our model

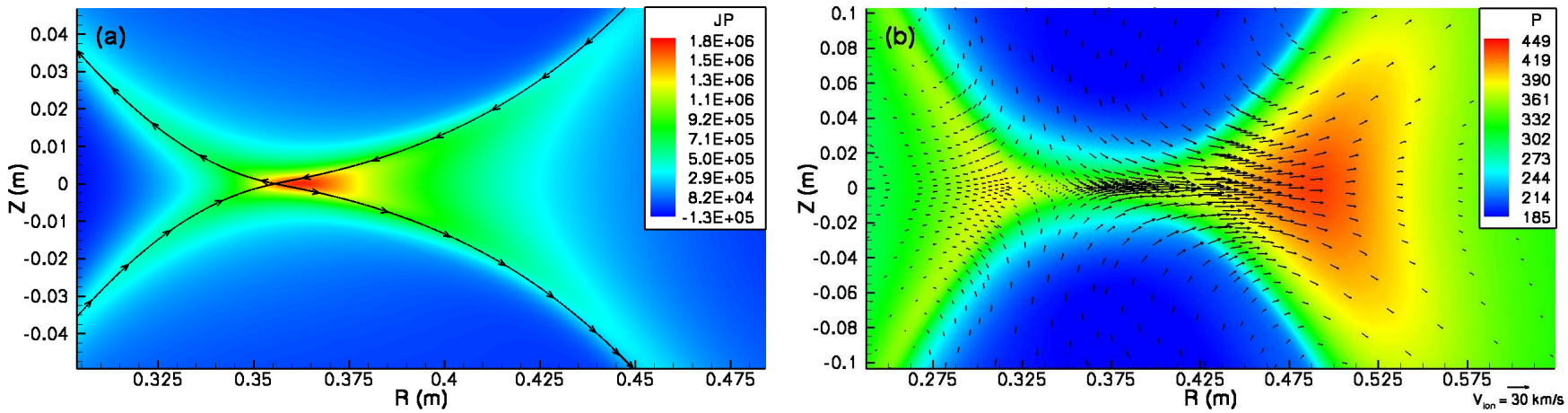
X-point motion is observed during spheromak merging in MRX





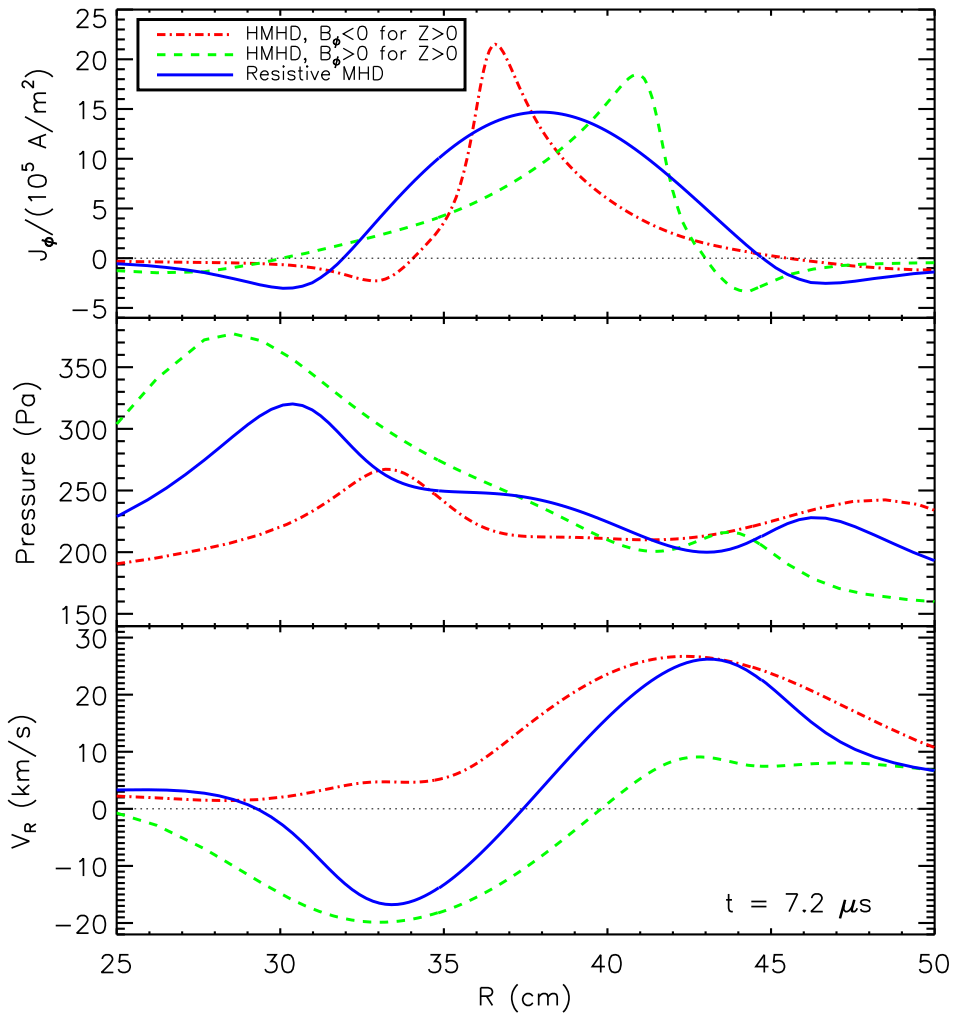
- Hall symmetry breaking is apparent when the orientation of the toroidal field is changed during two-fluid spheromak merging in MRX (Inomoto et al. 2006)
  - The reconnecting field lines are no longer based in the poloidal plane, so there is a radial component of electron velocity associated with the reconnection current
  - The radial component of electron outflow drags the reconnecting field lines in the poloidal plane, causing this radial shift in position of the X-point
  - Note, however, that because of axisymmetry this cannot be just a rotation of the standard 2D picture of quadrupole formation
- The Hall symmetry breaking causes asymmetric outflow patterns and downstream pressure, which we investigate in simulation

Counter-helicity simulations highlight the importance of tension forces



- The left plot shows out-of-plane current density contours with a magnetic field stream trace, and the right plot shows pressure contours with V_i vectors for a counter-helicity simulation of two-fluid push reconnection in linear geometry
- The current sheet position becomes shifted with respect to 37.5 cm and there is asymmetric outflow, in accordance with the results from Inomoto et al. (2006)
- Several effects contribute to asymmetric outflow
  - On the left, increased magnetic pressure impedes the outflow (Inomoto et al. 2006), and magnetic tension forces are reduced
  - On the right, magnetic tension forces are greatly increased due to the position of the X-point
  - Above and below, diamagnetic effects result in strong ion flow to the right

Toroidal symmetry breaking can act with or against Hall symmetry breaking



- The toroidal current density, pressure profile, and outflow velocity (seen at $Z = 0$) all depend on both toroidal and Hall symmetry breaking
- Symmetry breaking due to toroidicity and the Hall effect can work together or oppositely

Conclusions

- Due to the interaction of toroidicity and pressure effects, push and pull reconnection are examples of reconnection with asymmetries in the outflow and inflow directions, respectively
  - MRX has the potential to be a testing ground for theories of asymmetric reconnection (Cassak & Shay 2007), if pressure effects are included
- The reconnection process can feed back on itself via large scale pressure differences
- A radially inward drift of the current sheet during pull reconnection results from fast density depletion on the inboard side
- As a result of the density asymmetry due to toroidicity, the outboard quadrupole lobes peak closer to the X-point than the inboard quadrupole lobes
- In push reconnection, high inboard pressure pushes the X-point towards the outboard side of the current sheet, increasing inward-directed tension forces
- Hall MHD does not adequately describe the electron outflow profile
- The reconnection rate is affected more by the geometric mode of operation than by the inclusion of two-fluid effects
- Counter-helicity push reconnection results in asymmetric outflow due to multiple effects (magnetic pressure, tension, diamagnetic flows) and can work with or against toroidal symmetry breaking