NIMROD Simulations of Reconnection in MRX and SSX

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Outline

- A discussion of how to investigate local vs. global effects in reconnection
- Experimental setup of MRX
- Two-fluid global simulations of reconnection in MRX, including
  - Co-helicity runs producing a tilt in the current sheet
  - Counter-helicity runs with a radial shift in the current sheet
- Resistive MHD simulations of spheromak formation and merging in SSX

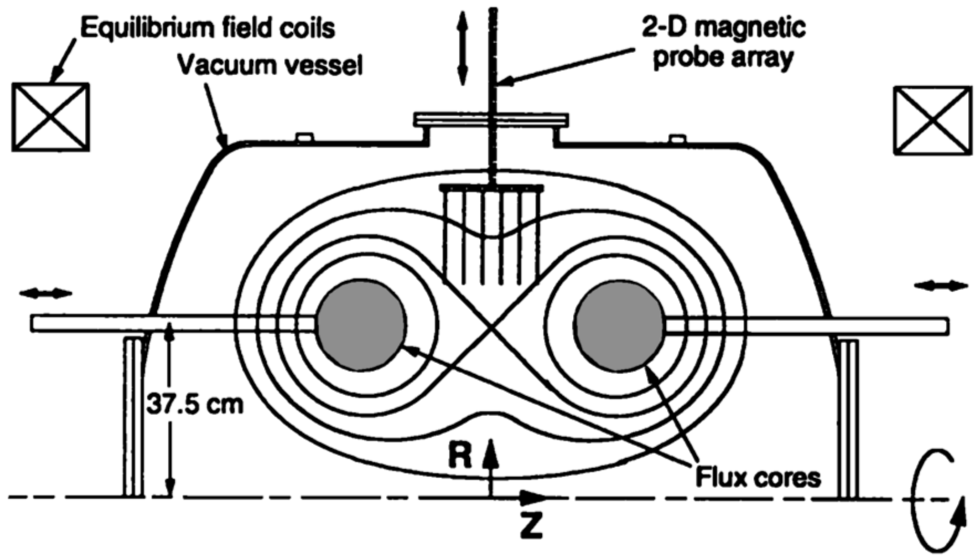
Motivation

- Most two-fluid studies of reconnection focus on local reconnection physics (e.g. Birn *et al.*, 2001), and most global studies have used resistive MHD (e.g. Lukin *et al.*, 2001)
- However, the reconnection layer can communicate with the global magnetic field via non-MHD waves
- Changes in the global magnetic field topology can in turn affect the reconnection rate
- NIMROD now has the capability to perform two-fluid global simulations in a realistic geometry and compare them to local idealized simulations
- Choosing MRX and SSX as global cases allows benchmarks to aid the simulation effort and provides computational support to the experiments

Local vs. Global Effects

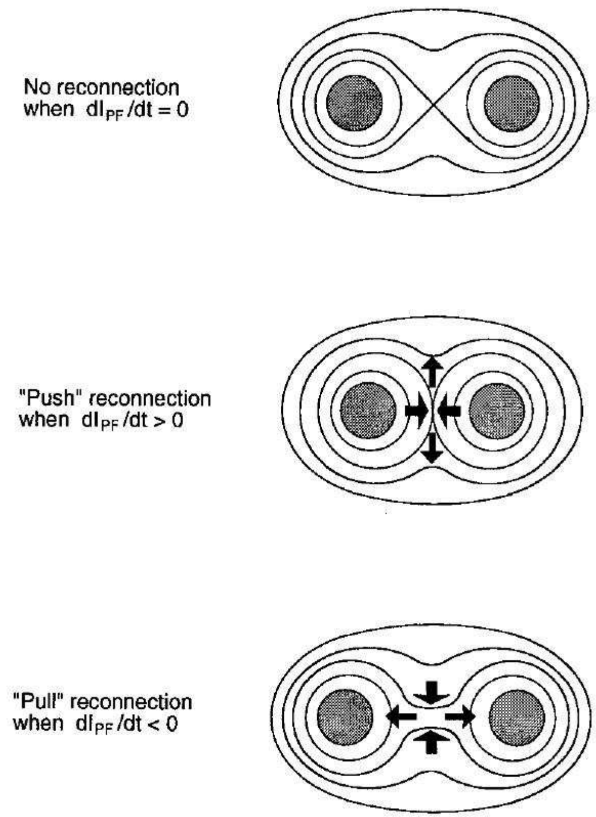
- Magnetic reconnection is influenced by global effects (length scales, driving forces, geometry) and local effects (wave-particle interactions, collisionality, Hall effects)
- The reconnection layer communicates with the global magnetic field through dispersive waves such as whistlers and kinetic Alfvén waves in addition to shear Alfvén waves
- This communication might regulate the reconnection process to ensure that reconnection occurs as fast as it is driven
- A strategy to gauge local vs. global effects is to take the fields from a global simulation to set up a local simulation and look for differences in the evolution of the plasma

The Magnetic Reconnection Experiment



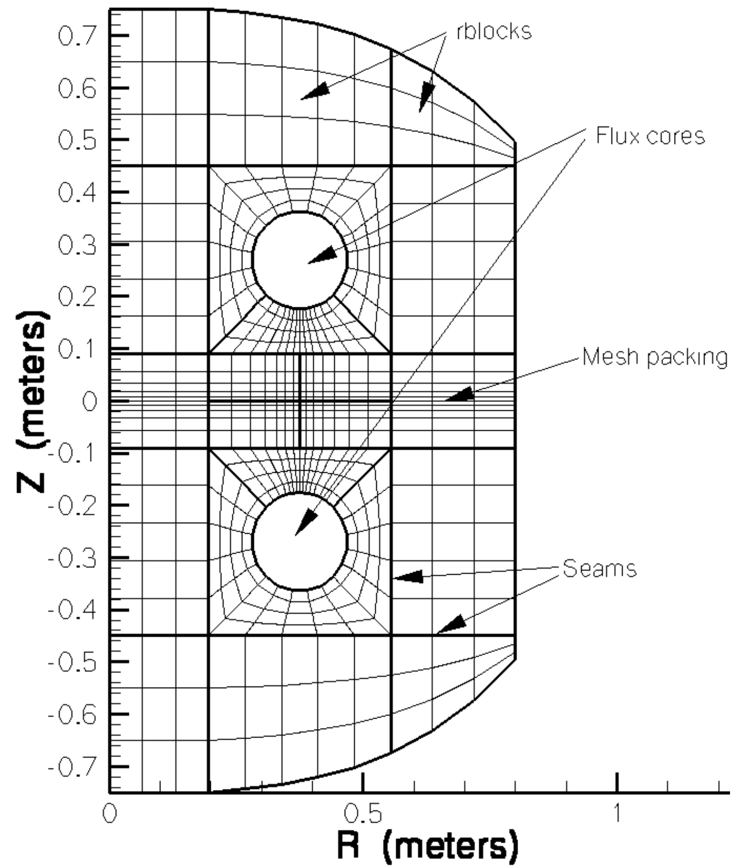
- The Magnetic Reconnection Experiment (MRX) is located at the Princeton Plasma Physics Laboratory and is designed to study controlled axisymmetric magnetic reconnection.
- Plasma parameters: $T \sim 15$ eV, $B \sim 200$ G, $S \sim 250 - 1000$, and $n \sim 10^{14}$ cm^{-3}.

MRX Modes of Operation



- By changing the currents in the flux cores, two distinct modes of reconnection can be induced in MRX (Yamada et al. 1997).

Finite Element Grid for MRX



- MRX has a nontrivial geometry which requires significant modification of NIMROD's preprocessing routines. Voltage is applied on the flux core surfaces to drive reconnection.

Non-Ideal Hall MHD Model

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

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

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

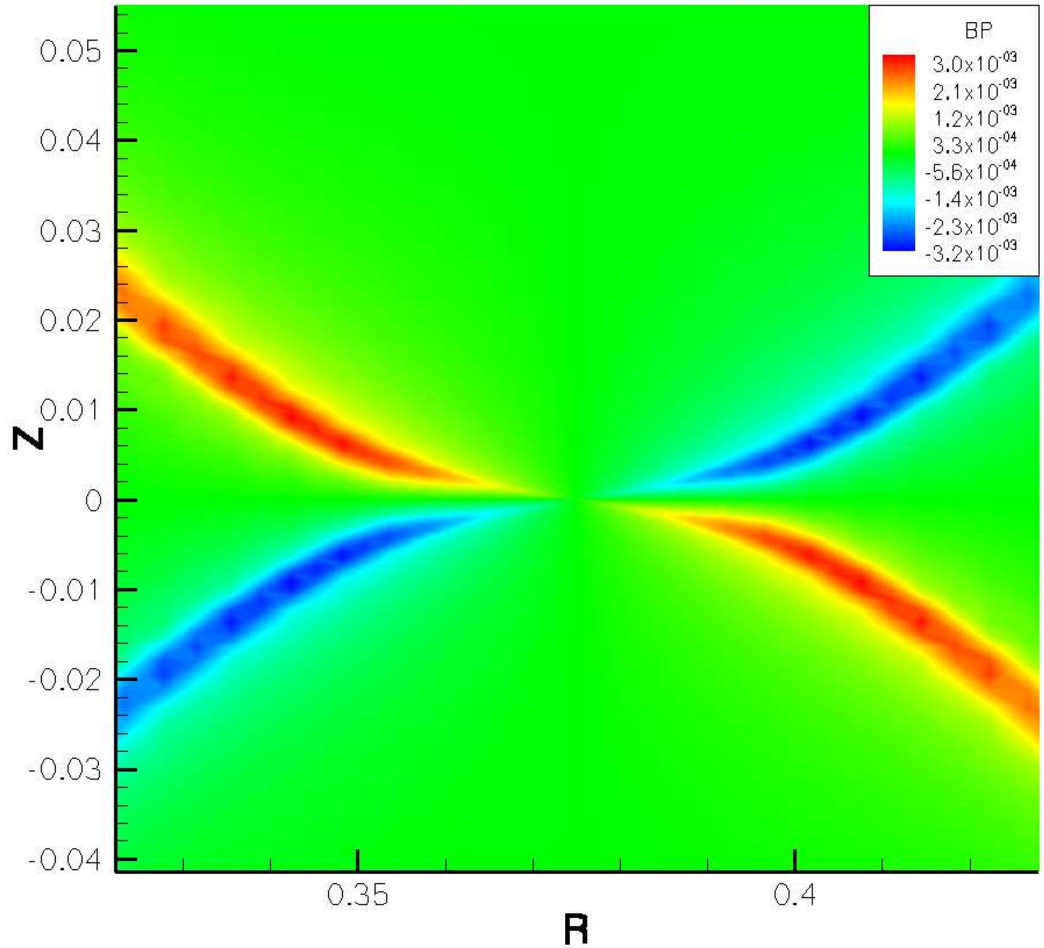
$$\nabla \cdot \mathbf{B} = 0$$

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

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

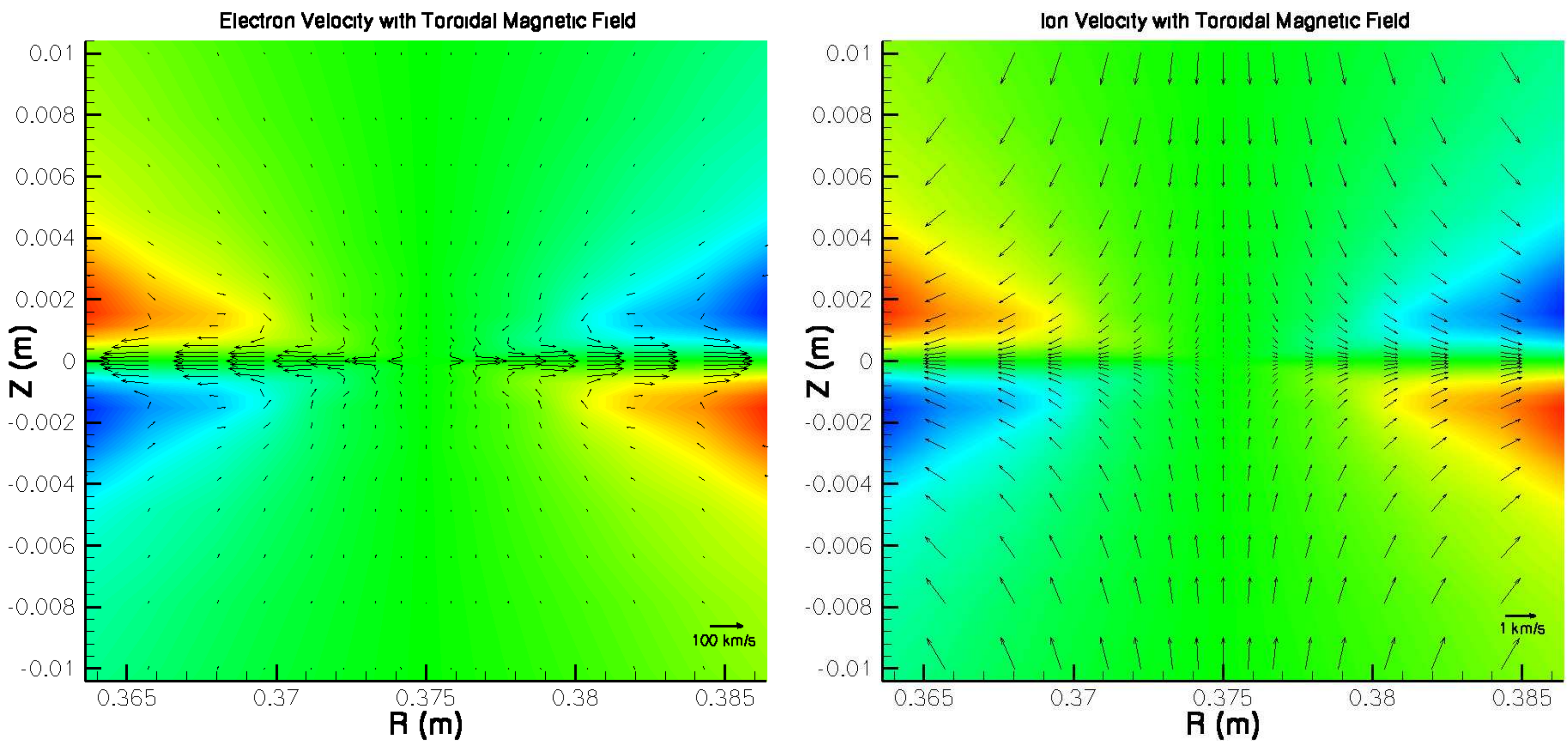
$$\frac{n}{\gamma - 1} \left(\frac{\partial T_\alpha}{\partial t} + \mathbf{V}_\alpha \cdot \nabla T_\alpha \right) = -p_\alpha \nabla \cdot \mathbf{V}_\alpha - \nabla \cdot \mathbf{q}_\alpha + Q_\alpha$$

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



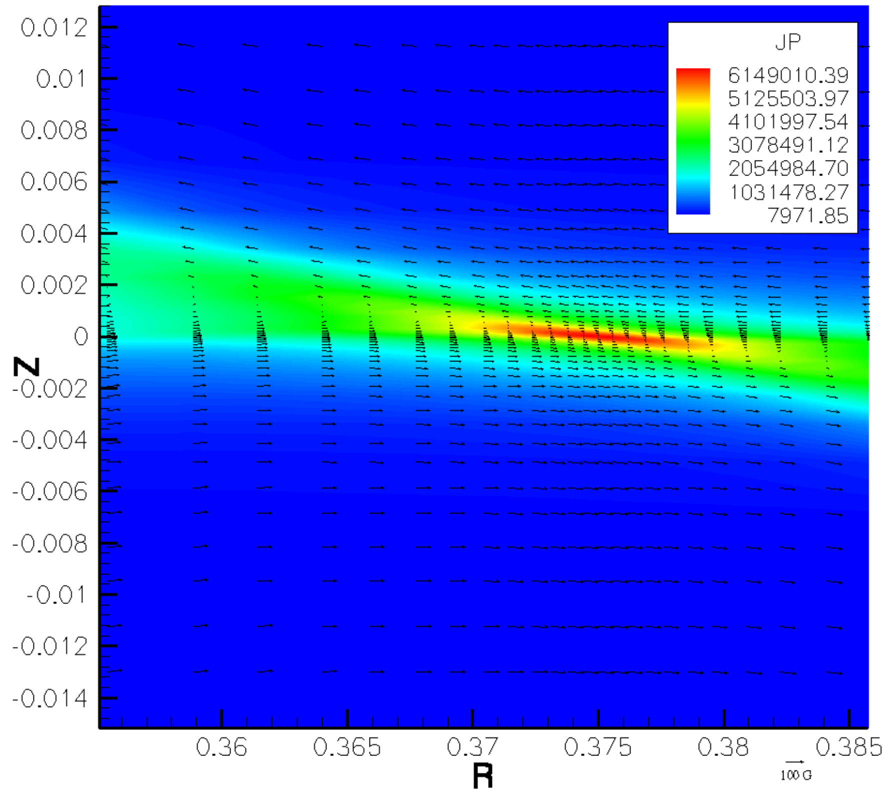
- Two-fluid push reconnection simulations in MRX's geometry show the development of the quadrupole field signature of whistler-mediated reconnection. Here, $S \sim 750$, $B_R \sim 60$ G and $c/\omega_{pi} \sim 4$ cm.

There is significant electron outflow on scales well below c/ω_{pi}



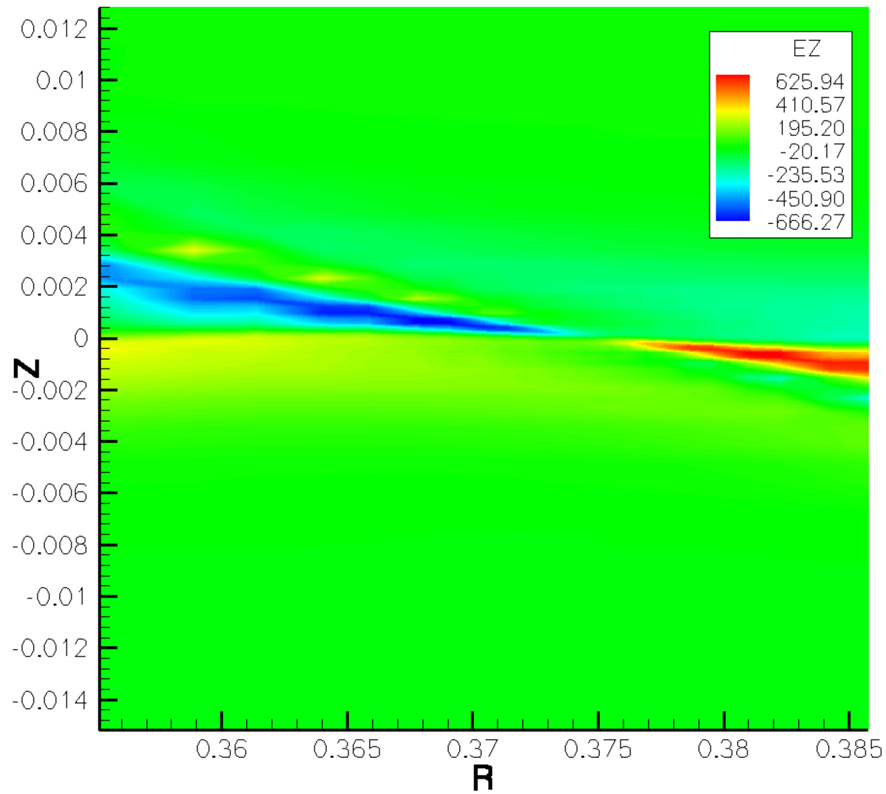
- The electron outflow is significantly more concentrated and at higher speeds than the corresponding ion outflows

The current sheet tilts during two-fluid co-helicity reconnection



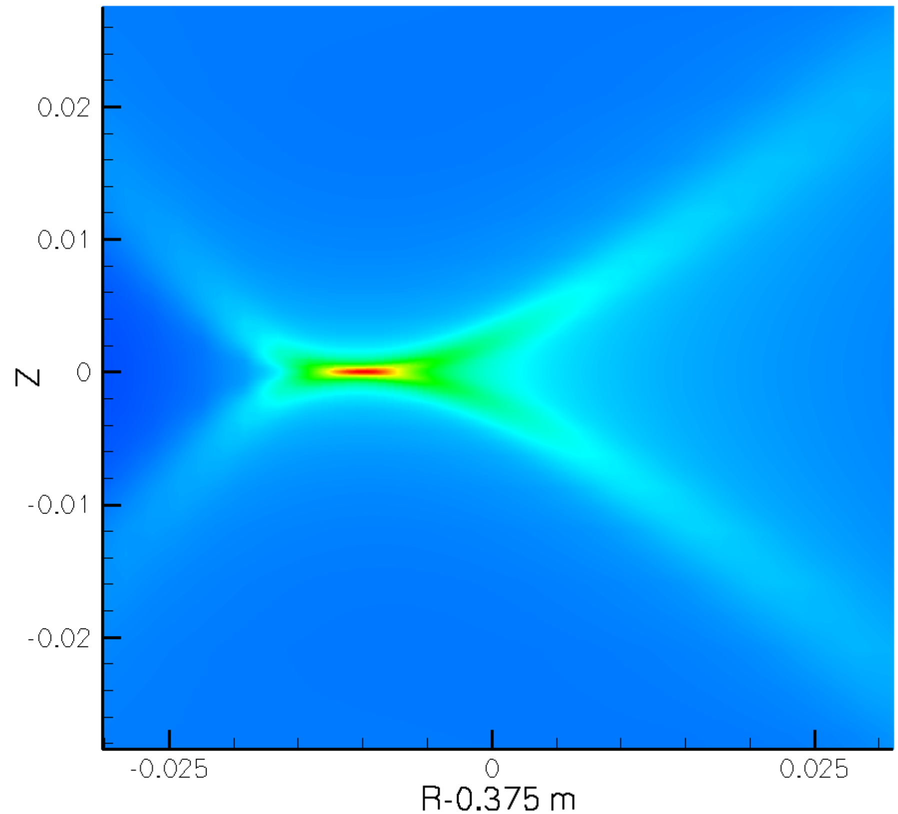
- Introducing a guide field during a two-fluid simulation breaks the symmetry. (J_ϕ contours and $\mathbf{B}_{pol}$ vectors)

The tilt is associated with a localized vertical Hall electric field



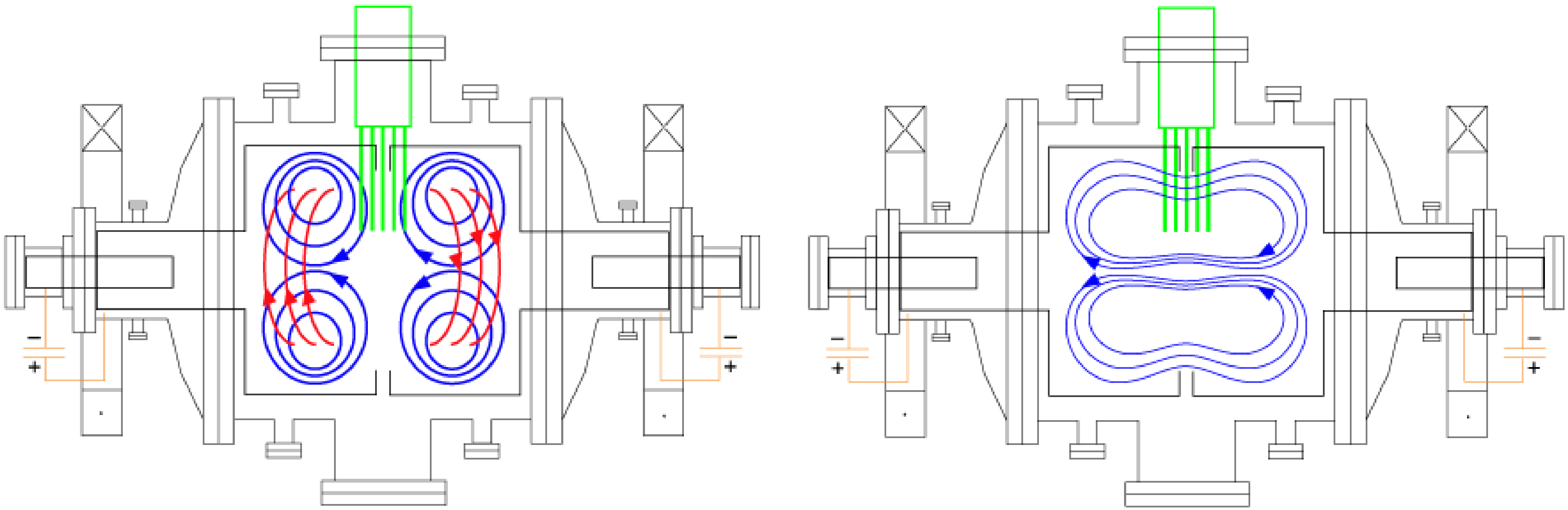
- In two-fluid null-helicity reconnection, there is a large inward-pointing current density corresponding to the localized electron outflow
- A guide field imposed on this setup would produce a significant vertical Hall $\mathbf{J} \times \mathbf{B}/ne$ electric field
- The magnetic field moves with the electrons, producing the tilt

A shift in position occurs during two-fluid counter-helicity merging



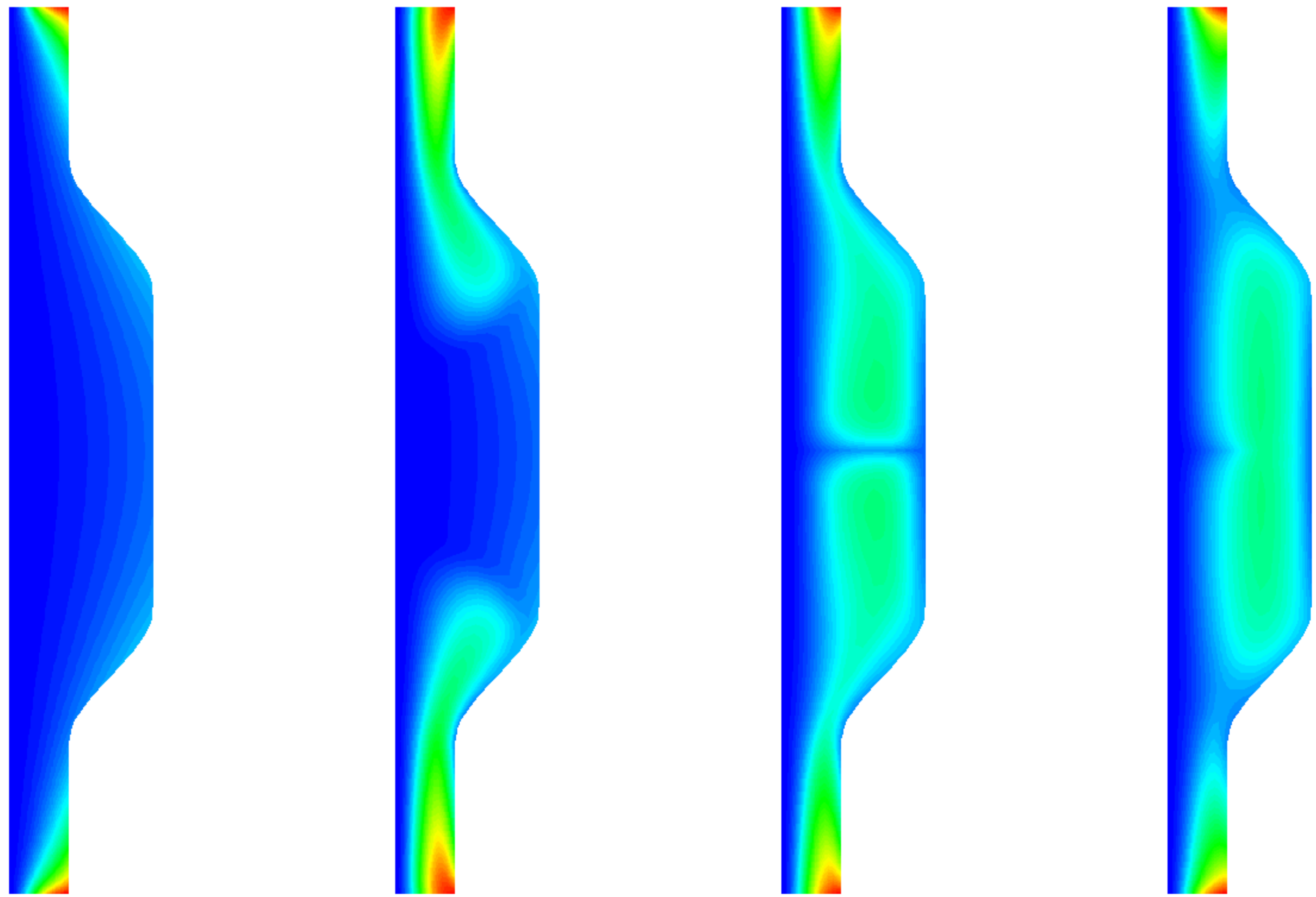
- An opposite shift is seen when the toroidal field directions are reversed (currently, B_ϕ is out-of-plane for $Z > 0$)
- A pressure buildup is observed on the side from which the current sheet was shifted
- See also Inomoto *et al.*, PRL, submitted and simulations by E. Belova

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 compact toroid tilts
- This setup is described by Cothran et al. (2003)

Poloidal flux contours show spheromak formation/merging in SSX



- This simulation is axisymmetric and uses resistive MHD. Initial two-fluid simulations do not yet show a quadrupole field.

Conclusions

- Two-fluid global simulations with realistic geometry are being performed with the intent of understanding the interplay between local and global effects
- Several two-fluid results are seen in global simulations of MRX
  - The tilt of the current sheet during two-fluid co-helicity reconnection is associated with a localized vertical component of the Hall electric field
  - There is an asymmetric pressure buildup associated with the radial shift in position during counter-helicity reconnection
- Simulations of SSX show spheromak formation and merging
- Direct comparisons to idealized local simulations of reconnection in the coming months will give us an opportunity to gauge how global and local effects interact to influence to reconnection process