# Simulating Magnetic Reconnection Experiment (MRX) with a guide field using fluid code, HiFi

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## Abstract

Magnetic reconnection is a phenomenon that occurs in plasmas when magnetic field lines effectively "break" and reconnect resulting in a different topological configuration. In this process, energy that was once stored in the magnetic field is transfered into the thermal velocity of the particles, effectively heating the plasma. MRX at the Princeton Plasma Physics Laboratory creates the conditions under which reconnection can occur by initially ramping the current in two adjacent coils and then rapidly decreasing said current, with and without a guide magnetic field, along the reconnecting current. We simulate this experiment using a fluid code called HiFi, an implicit and adaptive high order spectral element modeling framework, and compare our results to experimental data from MRX. The purpose is to identify physics behind the observed reconnection process for the field line break and the resultant plasma heating.

## Magnetic Reconnection Experiment (MRX)

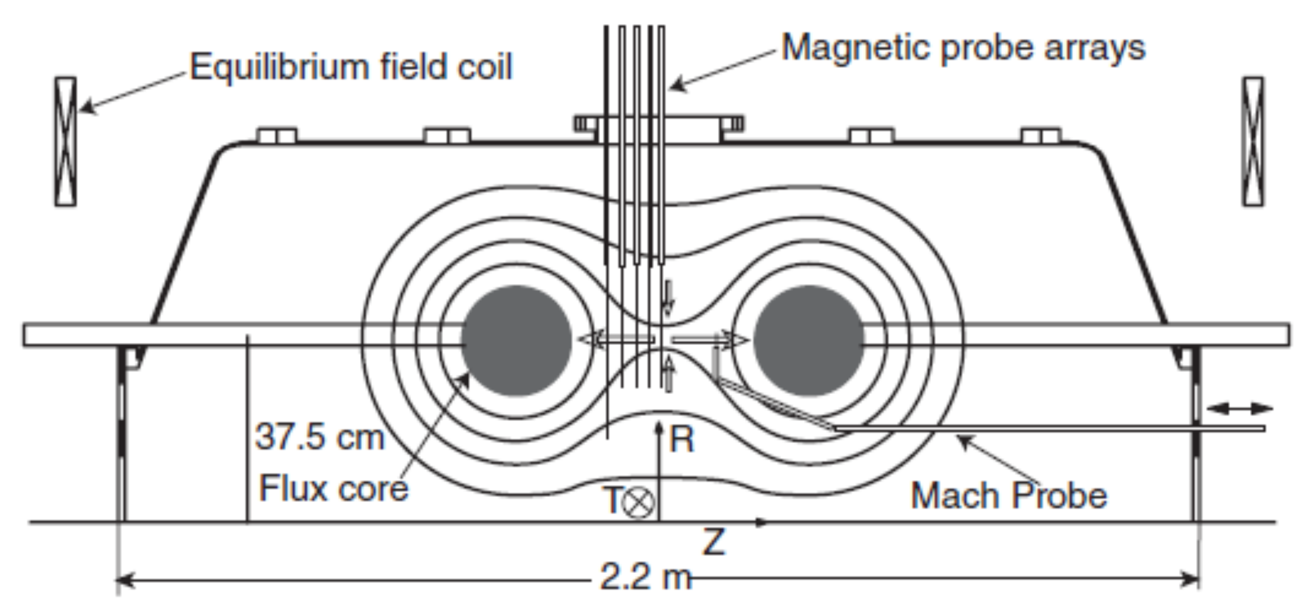
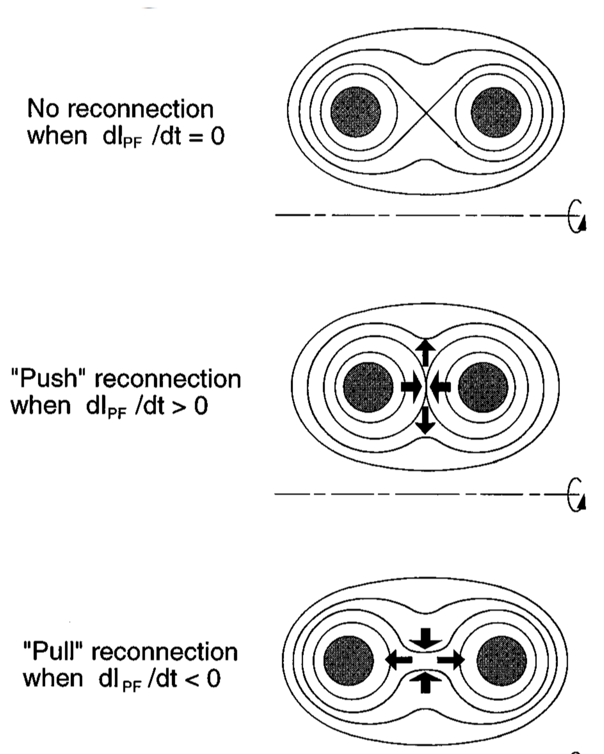



FIG 1. Cross-sectional view of MRX. In the physical experiment, the two flux cores wrap around the z-axis to form adjacent toruses. These are responsible for driving, and then decreasing, the current that creates the magnetic field geometry which allows for reconnection.

FIG 2. (below) A current profile over time of the current generated in the flux cores used to drive the magnetic reconnection event.



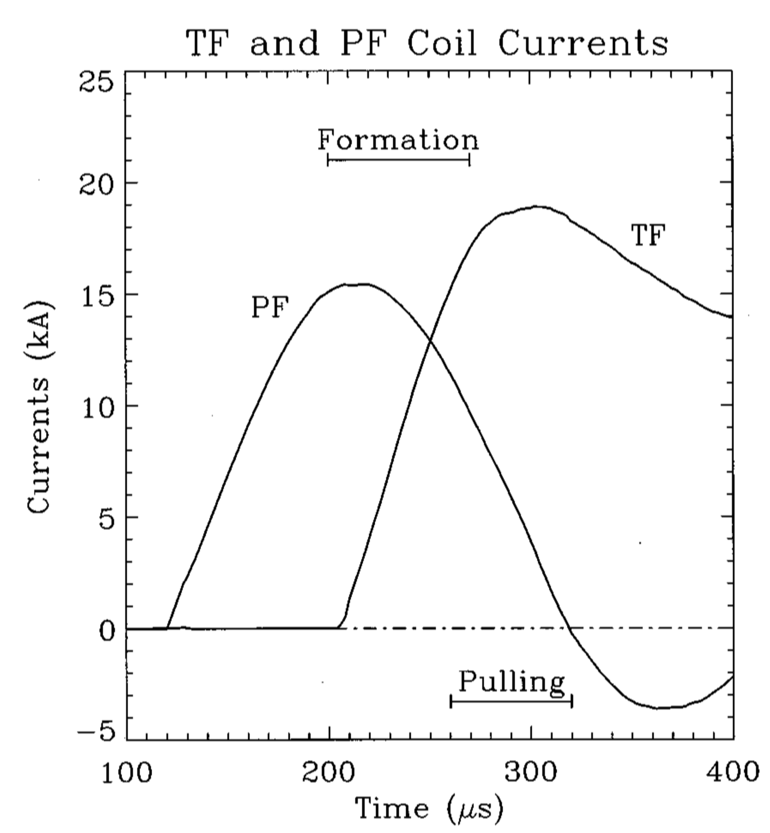




FIG 3. (above) When the current in the coils is increasing, we observe the "push" reconnection, and as it decreases, we observe the "pulling" phenomenon.

## Motivation and Goals

The experimental and theoretical work surrounding MRX is motivated by the desire to better understand the fundamental physics of reconnection phenomenon. Magnetic reconnection occurs in a variety of natural and astrophysical plasmas as well as in many fusion experiments. It also may provide insights into unsolved problems, such as coronal heating. The goal of this research as presented is to reproduce experimental results using the plasma simulation code HiFi.

## Experimental Data

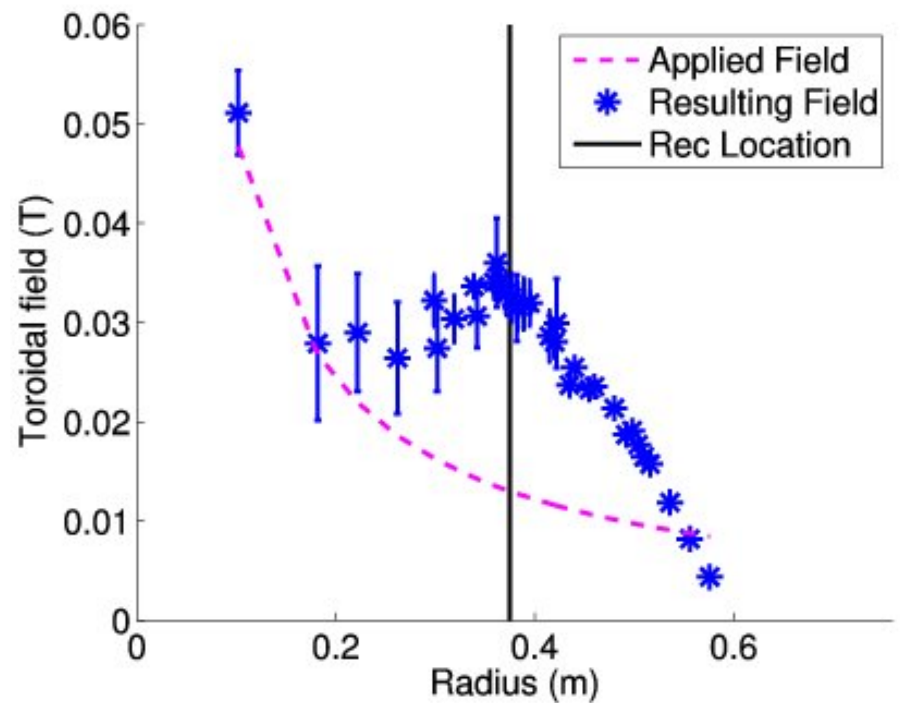



FIG 2. A profile of $B_\phi$ over the radial distance of MRX. A guide field of ~0.13 T at the center r = 0.35 m between the two coils. In the "pull" part of the reconnection, we observe the resulting magnetic field measured at various points in the experiment.

In simulating MRX, the guide field was incorporated into the program by using the applied field value at the center of the apparatus to calculate the current needed to generate the correct field using Ampere's law. This value in kiloamps was then added to parameters of the simulation.

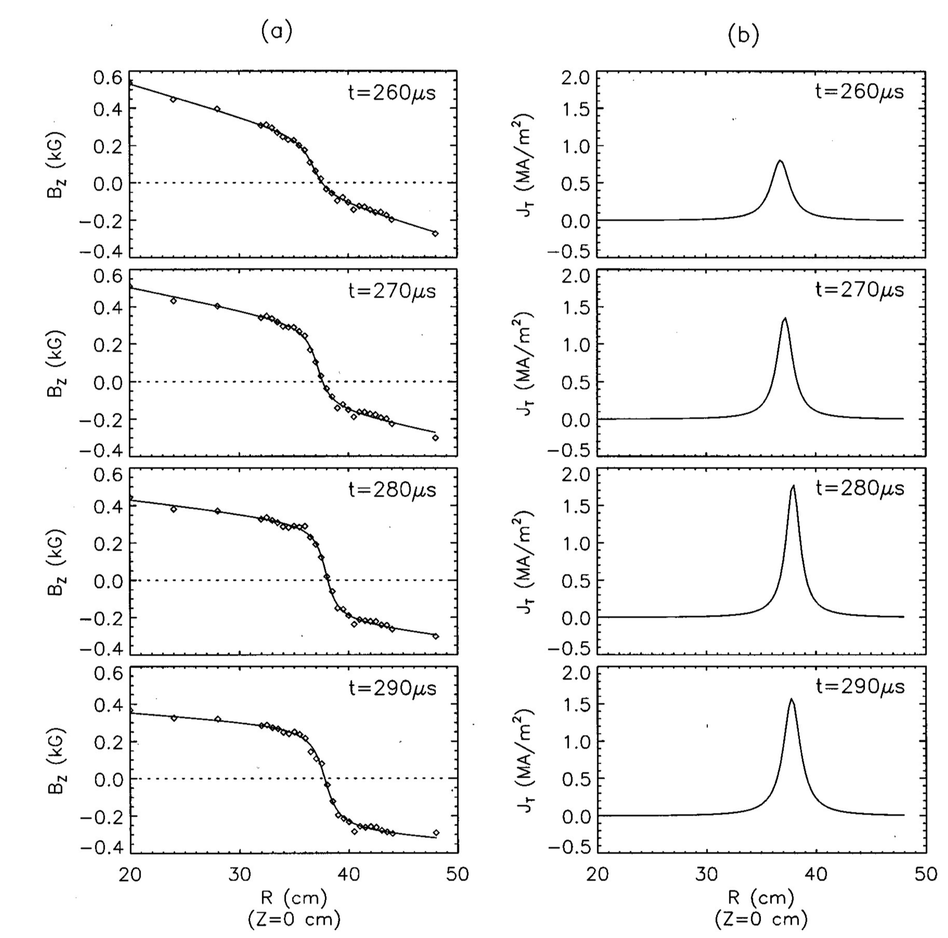



FIG 3a-b. Profiles of $B_z$ (a) and the toriodal current density (b) over the radial distance of MRX. In this experimental setup, there is no external guide applied to the plasma. We observe the z-component of the magnetic field evolving over time.

## HiFi

HiFi has a number of distinguishable qualities that make it an elegant and robust simulation code, including adaptive spectral element spatial representation with a flexible 3D geometry, highly parallelizable and implicit time advance, as well as a general flux-source form of the partial differential equations and boundary conditions that can be utilized by the HiFi framework.

| Eq | Equation | bottom | | top | | Left & right |
|---|---|---|---|---|---|---|
| | | ymin=0(no Bg) | ymin ≠0(with Bg) | ymin=0 | ymin ≠0 | |
| 1 | $\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{v}-D_n\nabla\rho)=0$ | $\frac{\partial\rho}{\partial y}=0$ | $\rho v_y=0$ (zero flux) | zero flux | ~ | $\rho v_x=0$ |
| 2 | $\frac{\partial\psi}{\partial t}+\nabla\cdot\left(-d_i\mu_e\frac{\nabla v_{ez}}{\rho}\right) = v_{iy}B_x-v_{ix}B_y-\frac{d_i}{n}(j_{iy}B_x-j_{ix}B_y)+\eta j_z - d_i\mu_e\frac{\nabla v_{ez}\cdot\nabla\rho}{\rho^2}$ | $\psi=0$ (static) | $\frac{\partial\psi}{\partial t}=0$ (conducting wall) | conducting wall | ~ | conducting wall |
| 3 | $\frac{\partial B_z}{\partial t}+\nabla\cdot\left(\begin{matrix}B_z\mathbf{v}_i-v_{ez}\mathbf{B}+\eta j_y\hat{x}-\eta j_x\hat{y}\\+\frac{\beta d_i}{n}\left((\nabla\cdot\vec{P})_x\hat{y}-(\nabla\cdot\vec{P})_y\hat{x}\right)\end{matrix}\right)=\nabla\cdot\left(\frac{d_i}{n}B_z\mathbf{j}\right) = d_iB_z\left(\frac{\partial}{\partial x}\left(\frac{1}{n}\right)j_x+\frac{\partial}{\partial y}\left(\frac{1}{n}\right)(j_y)\right)$ | $B_z=0$ (jx=0) | $B_z = \frac{\mu_0 I_c}{2}\frac{1}{ymin}$ (jx=0) | $B_z=0$ | $B_z = \frac{\mu_0 I_c}{2}\frac{1}{ymax}$ | $\frac{\partial B_z}{\partial x}=0$ |
| 4 | $\frac{\partial\rho v_x}{\partial x}+\nabla\cdot\left(\rho v_x\mathbf{v}+\left(\left(\frac{B_z^2}{2}+p\right)\hat{x}\right)-\mu\left(\nabla v_x+\frac{\partial}{\partial x}\mathbf{v}\right)\right)=-B_yj_z$ | $\frac{\partial}{\partial y}(\rho v_x/\rho)=0$ | ~ | $\frac{\partial}{\partial y}(\rho v_x/\rho)=0$ | ~ | $\rho v_x=0$ |
| 5 | $\frac{\partial\rho v_y}{\partial x}+\nabla\cdot\left(\rho v_y\mathbf{v}+\left(\frac{B_z^2}{2}\hat{y}\right)-\mu\left(\nabla v_y+\frac{\partial}{\partial y}\mathbf{v}\right)\right)=B_xj_z-\frac{\partial}{\partial y}p$ | $\rho v_y=0$ | ~ | $\rho v_y=0$ | ~ | $\frac{\partial}{\partial x}(\rho v_y/\rho)=0$ |
| 6 | $\frac{\partial\rho v_z}{\partial x}+\nabla\cdot\left(\rho v_z\mathbf{v}+\left(\left(\frac{B_z^2}{2}+p\right)\hat{z}\right)-\mu\left(\nabla v_z+\frac{\partial}{\partial z}\mathbf{v}\right)\right)=j_xB_y-j_yB_x$ | $\rho v_z=0$ | $\frac{\partial}{\partial y}(\rho v_z/\rho)=0$ | $\frac{\partial}{\partial y}(\rho v_z/\rho)=0$ | ~ | $\frac{\partial}{\partial x}(\rho v_z/\rho)=0$ |
| 7 | $j_z=(\nabla\times B)_z=\frac{\partial}{\partial x}B_y+\frac{\partial}{\partial y}(-B_x)=\nabla\cdot(B_y\hat{x}-B_x\hat{y})$ | $j_z=0$ | ~ | ~ | ~ | ~ |
| 8 | $\frac{\partial}{\partial t}\left(\frac{3p}{2}\right)+\nabla\cdot\left(\frac{5}{2}p\mathbf{v}+\mathbf{q}\right)=\mathbf{v}\cdot\nabla p-\mathbf{\Pi}:\nabla\mathbf{v}+\eta j^2$ | $\frac{\partial}{\partial y}T=0$ | ~ | ~ | ~ | $\frac{\partial}{\partial x}T=0$ |

FIG 6. Table of eight of the principle equations used to simulate the MRX plasma, including density, flux, magnetic field, current, and temperature. In fine-tuning our calculations, we examined the the physical boundary conditions in the experiment and derived the mathematical consequences to be put into the HiFi program.

## Simulation Results

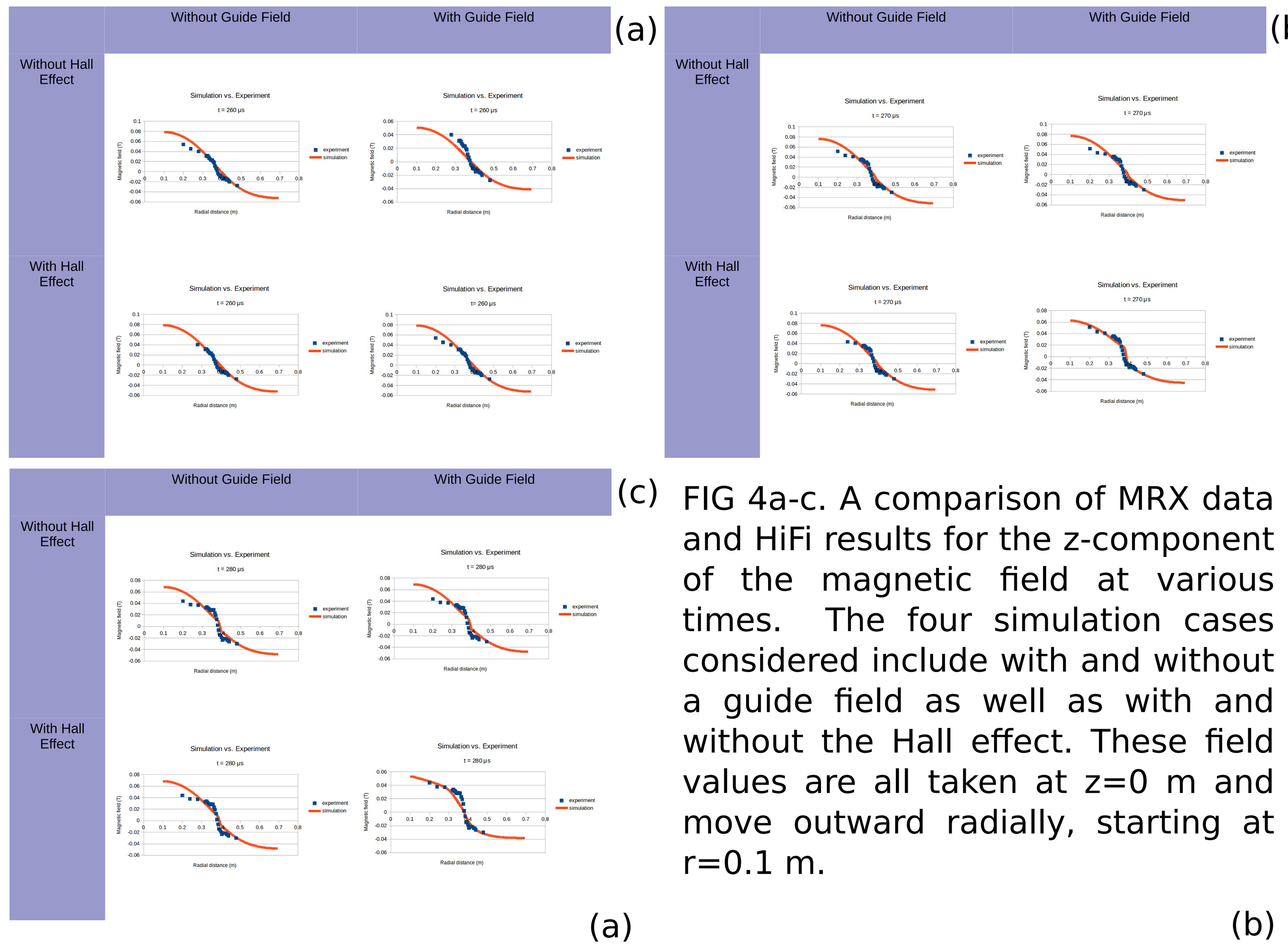



FIG 4a-c. A comparison of MRX data and HiFi results for the z-component of the magnetic field at various times. The four simulation cases considered include with and without a guide field as well as with and without the Hall effect. These field values are all taken at z=0 m and move outward radially, starting at r=0.1 m.

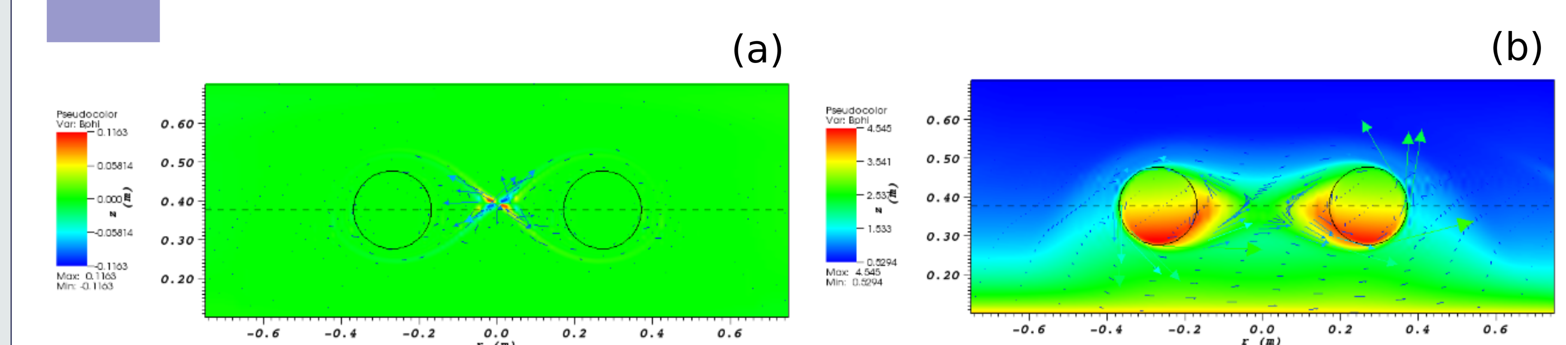



FIG 5a-b. False-color images of a simulated cross-section of MRX. The out-of-plane component of the magnetic field is plotted with guide field (b) and without (a). Here we consider the impact of including the Hall effect.

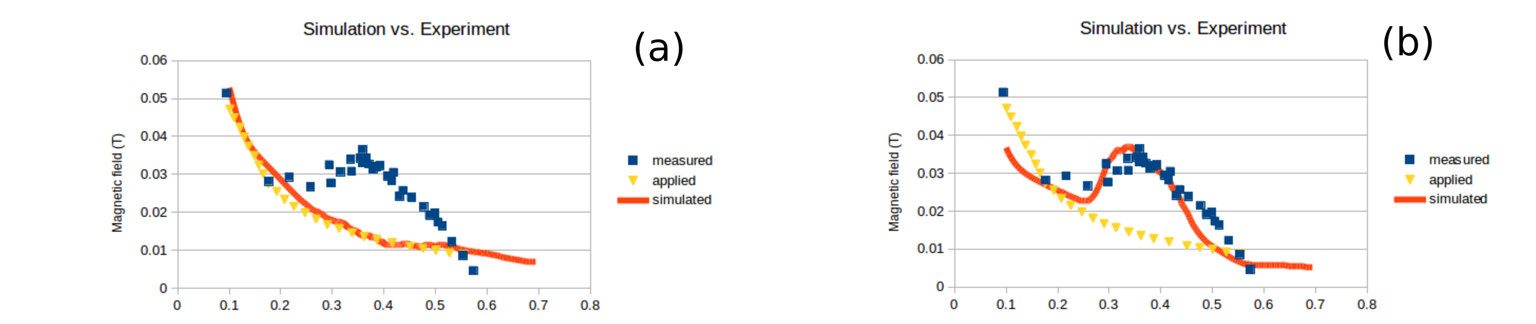



FIG 6a-b. A profile of the phi-component of the magnetic field is plotted and compared to experimental data. Without the Hall effect (a), we do not see very good agreement between simulation and experiment. However, with the Hall effect (b), we are able to reproduce the increase in field which deviates from the intial relation of B~1/r as shown by the "applied" field.

## Future Work

We would like to understand why a nonzero Hall term in Ohm's Law contributes so significantly the value of $B_\phi$ over the radial distance. We also would like to test how physical our simulated plasma is by analyzing temperature and density.

## References

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## Acknowledgements

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