Observations Supporting “Electron Hyper-Viscosity” Current Drive in the HIT-SI Spheromak

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Outline and Highlights

• Description and derivation of “electron hyper-viscosity” current drive

• Show expectation of increased electric field, increased power deposition in current drive region

• Bolometric data confirm increased power deposition with coupled magnetic fields, where electron hyper-viscosity is effective

• Phasing between coupling and electron flow predicts preferred spheromak current direction (two-fluid effect)

• Ion Doppler spectroscopy data show net ion velocities with driven current, consistent with electron hyper-viscosity model
Electron Hyper-Viscosity Differs from Hyper-Resistivity\textsuperscript{1,2} and Electron Locking\textsuperscript{3,4}

- Hyper-resistivity adds a new term to the Ohms law
  - Diffuses the $\lambda(\varphi)$ profile
  - Effect similar to adding electron viscosity
  - Does not use two-fluid effects

- Electron locking is locking electron flows across field
  - Uses two-fluid physics
  - Electron fluid is locked in rigid motion across separatrix

- In Electron Hyper-viscosity magnetic fluctuations cause an effective viscosity across magnetic field
  - Uses two fluid physics
  - Drag can be effective current drive without total locking
  - Fluctuation analysis justifies intuitive picture

\textsuperscript{1}Boozer A. H., J. Plasma Phys., \textbf{35}, 133 (1986)
\textsuperscript{3}Jarboe T. R., Nuclear Fusion, \textbf{41}, 679 (2001)
Two Models of Relaxation Current Drive

- In spheromaks, relaxation between dissimilar topologies drives current

- One Model: Reconnection
  - Requires only resistive MHD
  - Opening field lines

- Another Model: “Electron Hyper-Viscosity”
  - Requires two-fluid (Hall) resistive extended MHD
  - Drives current across closed flux

Figure: field line trace of injector driven flux and closed flux for Taylor state equilibrium, current amplification of 2, $\lambda = 10.3$.  

Figure credit: Chris Hansen
Derivation of Dynamo Current Drive

• Derivation uses pressureless, generalized Ohm’s law with Hall physics

• Resistivity allows slippage between magnetic field and electron fluid

• Derived from generalized Ohm’s law:
  • In inertial electron fluid frame:
    \[ E = \eta j \]
  • Lorentz transformation into laboratory frame:
    \[ E = -v_e \times B + \eta j \left( = -v \times B + \frac{j \times B}{ne} + \eta j \right) \]
  • Introduce perturbation:
    \[ B = B + \delta B \quad v_e = v_e + \delta v_e \]
Solve for Force Parallel to Mean Fields

\[ E + \delta E = -(v_e \times B) - (\delta v_e \times B) - (v_e \times \delta B) - (\delta v_e \times \delta B) + \eta j + \eta \delta j \]

- 1st Order
- 2nd Order

- Only 0th and 2nd order terms survive spatio-time averaging
- Only second order term yields current driving force parallel to \( v_e \) and \( B_0 \)

\[ E_{||} = -\langle \delta v_e \times \delta B \rangle_{||} + \eta j_{||} \]

- On HIT-SI, majority of current carried by electrons

\[ E_{||} \approx \frac{\langle \delta j \times \delta B \rangle_{||}}{ne} + \eta j_{||} \]
Think of Current Drive as Viscous Drag

• By nature of injector *driven* spheromak: \( \lambda \) in injector driven region greater than \( \lambda \) in closed flux region \( \rightarrow \) \( \mathbf{v}_e \) gradient

• Perturbation modes (black ellipses) between regions will be stretched by sheared \( \mathbf{v}_e \) flow

• Mode stretching opposed by field line tension

• Resulting effect is *viscous drag* between regions

• “Electron hyper-viscosity”:
  • Current drive in closed flux
  • Anti-current drive in injector driven region
B-Fields must be Coupled (Parallel)

- Use Taylor state equilibrium calculations to find regions with most coupling
  
  - Coupling = $\mathbf{B}_{\text{injector}} \cdot \mathbf{B}_{\text{spheromak}}$

- Larger region of **positive coupling** in front of left injector opening at this time slice

- Calculation for **opposite phase** of injector cycle shows **positive coupling** in front of right injector opening

- Electron hyper-viscosity current drive region **localized**

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*Figure: coupling calculations for spheromak ($\lambda = 10.3$) and upper injector ($\lambda = 16$)*

*Figure credit: Chris Hansen*
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Figure: coupling calculations for spheromak (\( \lambda = 10.3 \)) and upper injector (\( \lambda = 16 \)). Each Calculation uses opposite injector current direction.

Figure credit: Chris Hansen
Dynamic Impedance in Hyper-Viscosity Region → Localized Power Deposition

• In electron hyper-viscous current drive region, $E_{\parallel}$ must increase to overcome anti-current drive dynamo term

$$E_{\parallel} \approx \frac{\langle \delta j \times \delta B \rangle_{\parallel}}{ne} + \eta j_{\parallel}$$

• HIT-SI injectors induce loop voltage ($V_{\text{INJ}}$) → increased $E_{\parallel}$ in dynamo region yields greater relative voltage drop

• Larger voltage drop in current drive region suggests greater power deposition.
Measure Power from Volume in front of Injector Mouth

- Bolometer views region where injector driven fields and spheromak fields interact
- Hypothesize: greater $E_{||}$ in dynamo current drive region $\rightarrow$ greater voltage drop $\rightarrow$ more power deposited $\rightarrow$ more radiation measured
- Measured radiation should be higher at coupling half-cycle of injector phase

- Changing direction of spheromak current changes sign of coupling $\rightarrow$ reversal of toroidal current changes coupling phase by 180°

*Figure: machine cutaway of HIT-SI spheromak region and injector. Bolometer on right with viewing cone highlighted.*

*Figure credit: Mark Chilenski*
Increased Radiation in Phase with Calculated Coupling

- Radiation changes phase when $I_{TOR}$ changes direction

Bolometer Viewing Injector Mouth Region

Graph showing Bolometer Signal [Arb.] over time [ms]

- Bolometer Signal [Arb.]
- $I_{INJ}$ [kA]
- $I_{TOR}$ [kA]

Shot number 117501
Coupling Parameter Predicts
Spheromak Current Preferred Direction

• Empirically found: injectors tend to drive spheromak current in one direction only

• Direction of electron flow (drift velocity) in or out of injectors set by phase of injector cycle

• Location coupling region also set by phase of injector cycle, but can be switched by 180° by reversing toroidal current
• Coupling region occurs locked in phase either with electrons flowing into injector mouth or out of injector mouth, depending on toroidal current direction

• Claim greater $v_e$ gradient & more efficient current drive when electrons exiting injector mouth
  • Once electrons have traveled through confinement region, $v_e$ gradient will be diminished

• Preferred spheromak current direction is sign of toroidal current which phases coupling region with electrons exiting injector
Net Ion Force Drives Ions in Direction of Injector Driven Current

- For diagnostic purposes, examine effect of electron hyper-viscosity current drive on ions in injector driven region

- Recall increased $E$ in hyper-viscosity current drive region because electrons must overcome anti-current drive and collisional drag:

\[
E_{||} = \frac{\langle \delta j \times \delta B \rangle_{||}}{ne} + \eta j_{||}
\]

- Ions do not directly respond to hyper-viscous term $\rightarrow$ net force

\[
E_{||} > \eta j_{||}
\]

- Use Ion Doppler Spectrometer to measure velocities out of injector opening.

- Higher ion flow velocity in direction of injector loop voltage ($E$-field)
Data Predicts Peak $v_i$ at Peak $E_{||}$

Induced $E$-field from $-V_{\text{INJ}}$ drives ions out of injector (positive velocity on plots)
Ion Doppler Spectrometer Data
Support Electron Hyper-Viscosity Effects

Ion Doppler Spectrometer viewing Injector Mouth

- Ion velocity exiting injector in phase with $E$-field out of injector

Instrument on loan from M. Nagata
Shot number 117688

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Aaron Hossack, ICC Workshop
**Summary**

- Data presented are consistent with electron hyper-viscosity current drive
  - Bolometric data confirm increased radiation from regions with calculated coupling

- Preferred spheromak current direction consistent with dynamo current drive because electrons coming out of the injector produce higher current drive than electrons entering

- Dynamo produced net force on ions drives ions parallel to the current in the injector driven region

- **Future Work**: resolve ion velocities in closed flux region
  - No $E$-field inside separatrix, only force on ions collisional with electrons $\rightarrow$ expect ions flow with electrons (against $I_{TOR}$)