Internal Magnetic Structure and Electric Fields in the Helicity Injected Torus with Steady Inductive Helicity Injection (HIT–SI)

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Talk Outline

• HIT–SI Background

• Spheromaks with $I_{\text{TOR}}=29$ kA, $I_{\text{TOR}}/I_{\text{INJ}}=1.5$

• Taylor-State Model Matches Field Evolution

• Internal $E$-Field Measurements
Helicity Conservation Makes Current Drive Simple

- Magnetic helicity is the best constant of motion in a magnetized plasma.

- Helicity-conserving magnetic activity dissipates free energy by producing a more uniform $J/B$ profile:
  Driving $J/B$ high in an experimentally convenient location produces current drive throughout the volume.

- If the fluctuation levels are limited to that required for current drive, then confinement in a high-conductivity reactor-scale plasma will not be overly degraded.
The HIT–SI Device

In each injector, flux and voltage are sinusoidal and in phase.

Total Helicity Injection Rate is

\[ \dot{K} = 2V_{INJ}\psi_{INJ} \sin^2 \omega t + 2V_{INJ}\psi_{INJ} \cos^2 \omega t = 2V_{INJ}\psi_{INJ} \]
HIT–SI is the Application of SIHI to Form and Sustain a Spheromak

- The HIT–SI confinement region has a “bow-tie” shape for improved stability and high $\beta$.

- HIT–SI has two inductive helicity injectors, which allows constant rates of helicity and power injection.

- The AC fields, voltages, and currents in the two injectors form and sustain a DC magnetized plasma (a spheromak), with significant toroidal current and field.
HIT-SI Diagnostic Locations

- Mid-plane diagnostic ports
- "X" Injector
- "Y" Injector
- Surface Probe
- Axial Port
- Internal Probe Array
Spheromak Formation with Toroidal Current of 29 kA
High Current HIT–SI Shot #105914
Spheromak Formation with Toroidal Current of 29 kA
High Current HIT–SI Shot #105914

Peak $I_{TOR}/I_{INJ}$ was 1.4; Axisymmetric $B_p$ matches Taylor-state distribution

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“Internal Magnetic Structure and Fields in HIT–SI”
HIT–SI Taylor-State Equilibrium Model

• Taylor-state basis functions are solutions to $\nabla \times \mathbf{B} = \lambda \mathbf{B}$

• HIT–SI Taylor-state equilibrium model uses three basis functions:
  * The lowest-energy (spheromak) eigenstate ($\lambda = 10.4 \, m^{-1}$)
  * Two injector-driven basis functions (undetermined $\lambda$)

Choose $\lambda = 10.4 \, m^{-1}$ for all three basis functions
$\Rightarrow$ Superposition is Taylor-State equilibrium

• The two injector-driven basis function amplitudes are scaled by the measured current in each injector.
  One free parameter: the spheromak eigenfunction amplitude.
Axisymmetric $B_p$ Scales Spheromak Eigenfunction

Comparison to experiment: HIT–SI discharge #105278.

Axisymmetric fields calculated from poloidal flux loops: Inboard loops at left, Outboard loops at right.

Black: experimental values
Red: scaled Taylor model

At each time step, the spheromak amplitude (a single parameter) provides the best fit to the axisymmetric fields.

\[
\text{discrepancy} \equiv \frac{1}{N} \sum_{N} \frac{|B_{\text{model}} - B_{\text{meas}}|}{|B_{\text{meas}}|}
\]

Eigenfunction by G. Marklin
Calculations by P. E. Sieck

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Model Matches Internal HIT–SI Fields

Comparison to experiment: HIT–SI discharge #105278.

Poloidal and Toroidal fields measured with internal array: Poloidal fields at left, Toroidal fields at right.

Bottom probe is deepest, at \( R = 0.36 \) m.
Top probe is near edge, at \( R = 0.52 \) m.

Black: experimental values
Red: scaled Taylor model

Slowly-varying spheromak amplitude also plotted, in red.

Basis functions by G. Marklin
Calculations by P. E. Sieck
Measurements by R. J. Smith
Model Matches Surface HIT–SI Fields

Comparison to experiment: HIT–SI discharge #105278.

Poloidal and Toroidal fields measured at inboard surface:
Poloidal fields at left, Toroidal fields at right.

Illustrates significant poloidal and toroidal variations in the surface fields.

Black: experimental values
Red: scaled Taylor model

Slowly-varying spheromak amplitude also plotted, in red.

Basis functions by G. Marklin
Calculations by Paul E. Sieck
Measured Fields in HIT–SI Discharge Database

Well-Fit by Taylor-State Model

- All HIT–SI discharges can be fitted by this Taylor-state model.
- The fit between measurements and the model improves with increasing toroidal plasma current $I_{\text{TOR}}$.


- Taylor-state model can also be used to trace field lines, for visualizing the equilibrium geometry.
Taylor-State Equilibrium Field Lines
Viewing one-half of HIT–SI, along symmetry axis

Injector-only fields

Injector and spheromak
$I_{\text{TOR}} / I_{\text{INJ}} \approx 1.5$

Injector and spheromak
$I_{\text{TOR}} / I_{\text{INJ}} \approx 5.0$

Separatrix formation occurs if $I_{\text{TOR}} / I_{\text{INJ}} \geq 1.0$

See also Jarboe et al., PRL 97, 115003 (2006).

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Internal E-Field Measurements Reveal the Voltage Dissipated in the Injectors

- Arrays of voltage probes are installed at the mouths of one HIT–SI helicity injector (the X-injector).
- These probes provide a direct measurement of the voltage drop within the confinement region.
- This measured voltage drop can then be compared to the total inductive loop voltage in the injector.
Injector Probe Located at Injector Mouth
HIT–SI Discharge #106136, Helium gas, Axial Window View
Spheromak Driving Voltage
Increases Linearly with Injector Loop Voltage

Measurements by Rabih Z. AboulHosn

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Conclusions

- HIT–SI demonstrates that SIHI can form and sustain spheromaks with $I_{\text{TOR}} \leq 29 \text{kA}$, using less than 6 MW of injected power.

- The spatial structure and temporal evolution of the fields in HIT–SI are well-described by a Taylor-state equilibrium model. Taylor-state model predicts separatrix formation at $I_{\text{TOR}} \approx I_{\text{INJ}}$. Experimentally, HIT–SI has demonstrated $I_{\text{TOR}} = 1.5 \times I_{\text{INJ}}$.

- Internal electric field measurements show that the injector voltages extend into the confinement region, and can thus drive the spheromak.