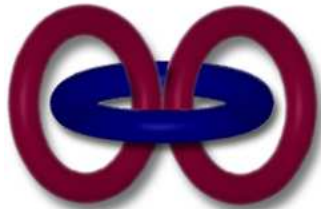


# Spheromak Formation by Steady Inductive Helicity Injection

Aaron J. Redd  
for the  
HIT Team



*Aerospace & Energetics Research  
University of Washington  
Seattle, Washington USA*



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## HIT Personnel

### *Faculty and Staff*

Thomas R. Jarboe	George R. Andexler	Luisa Pareja-Klemisch
Brian A. Nelson	Andrew Cassidy	Dennis Peterson
Roger Raman	Matthew B. Fishburn	John A. Rogers
Aaron J. Redd	Susan Griffith	Dzung Tran
Roger J. Smith		
George J. Marklin (PSI-Center)		Paul E. Sieck (LANL)

### *Graduate Students*

Rabih Z. AboulHosn	William T. Hamp	Bret T. Stewart
Cihan Ackay	R. “Griff” O’Neill	Jonathan Wrobel

### *Undergraduates*

Hok Chan	Breana Merriweather	Ling-Cheong Yu
Mark Chilenski	James Newman	

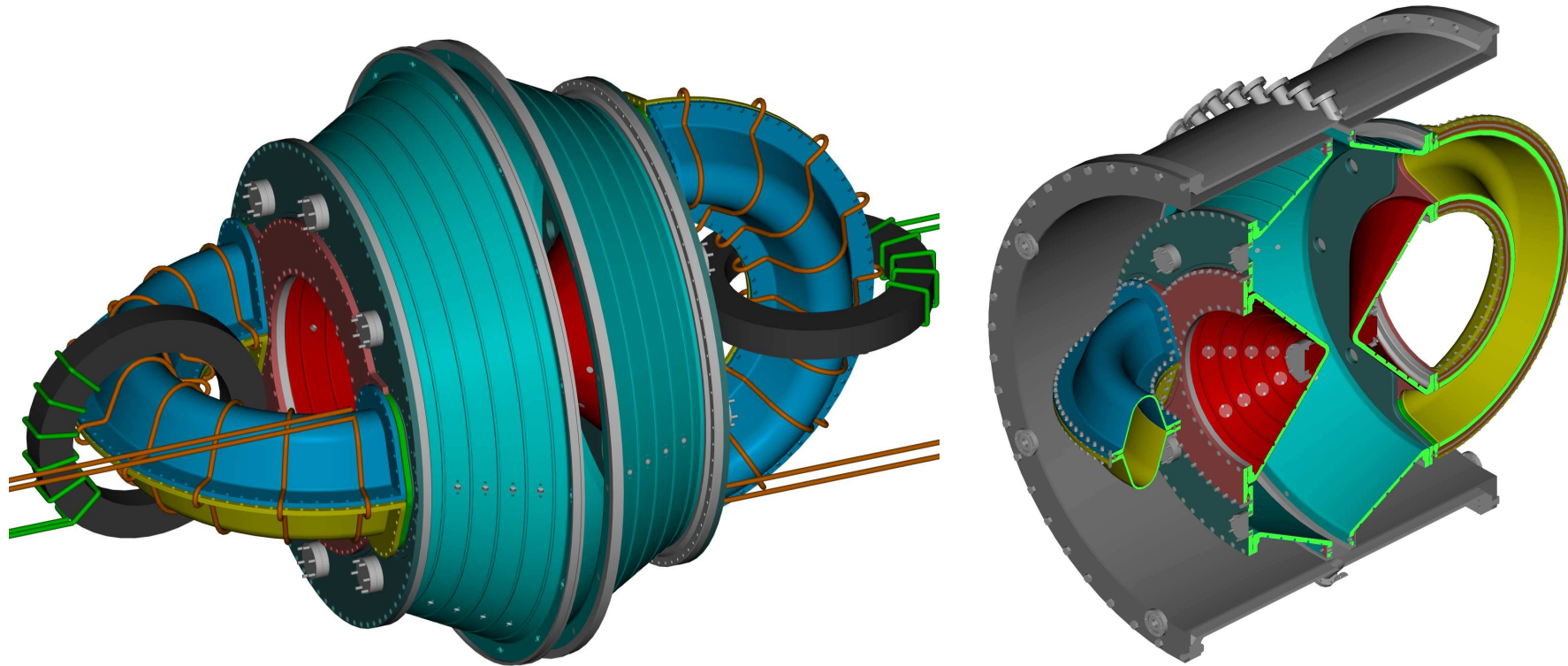
## Main Points

- The HIT–SI Device
- Spheromak Formation with  $I_{\text{TOR}}=29$  kA
- Magnetic Field Evolution matched by Taylor-State Model
- Internal **E**-Field Measurements

## HIT–SI Context

- Helicity Injection Current Drive is simple to implement, energetically efficient, and inherently steady-state.
- Steady Inductive Helicity Injection (SIHI) does not require significant plasma-wall interactions.
- Spheromaks are compact toroidal magnetized plasmas with a relatively simple “first wall”.
- HIT–SI is the application of SIHI to a spheromak.

## The HIT–SI Device



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

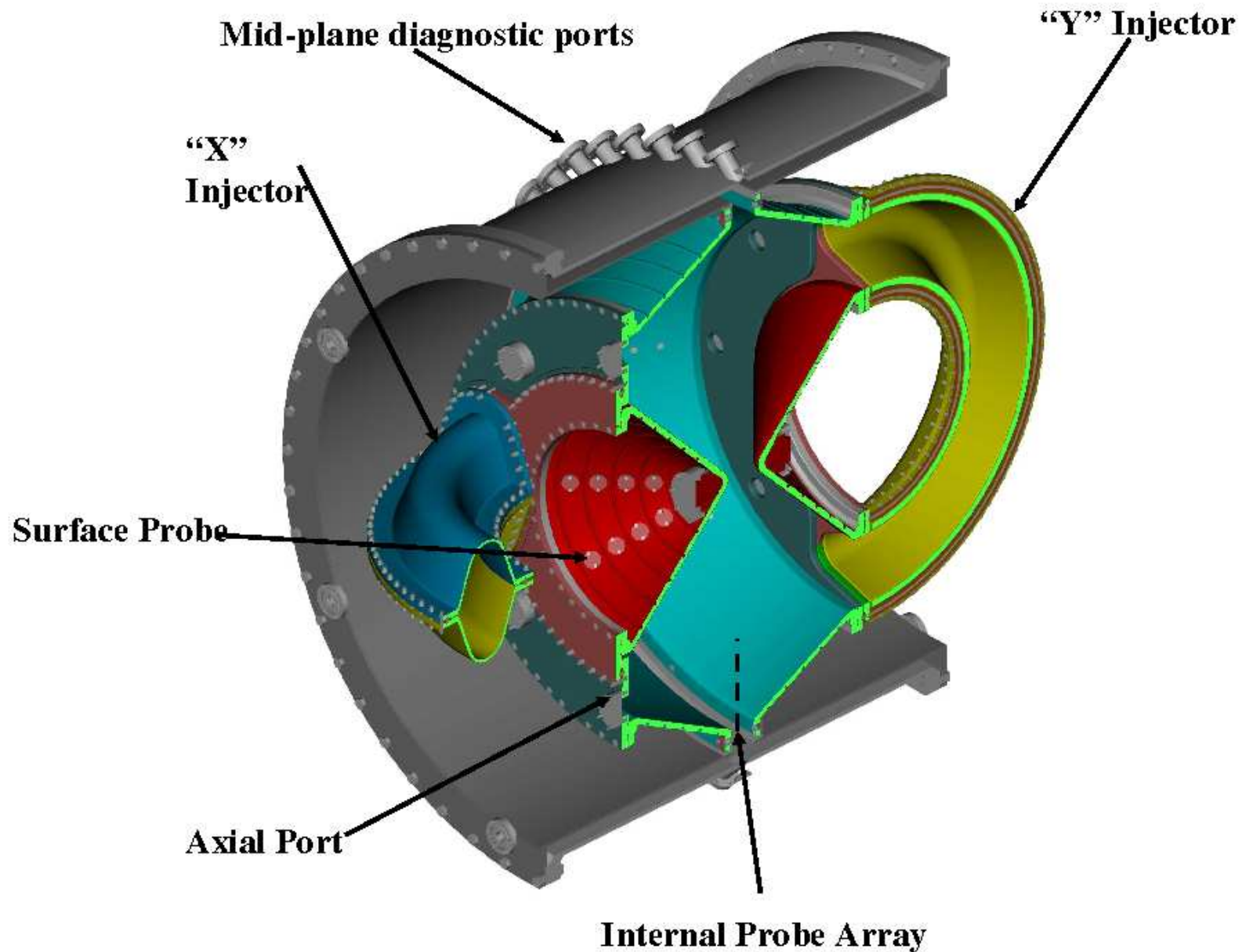
Total Helicity Injection Rate is

$$\dot{K} = 2V_{\text{INJ}}\psi_{\text{INJ}} \sin^2\omega t + 2V_{\text{INJ}}\psi_{\text{INJ}} \cos^2\omega t = 2V_{\text{INJ}}\psi_{\text{INJ}}$$

## HIT–SI is the Application of SIHI to Form and Sustain a Spheromak

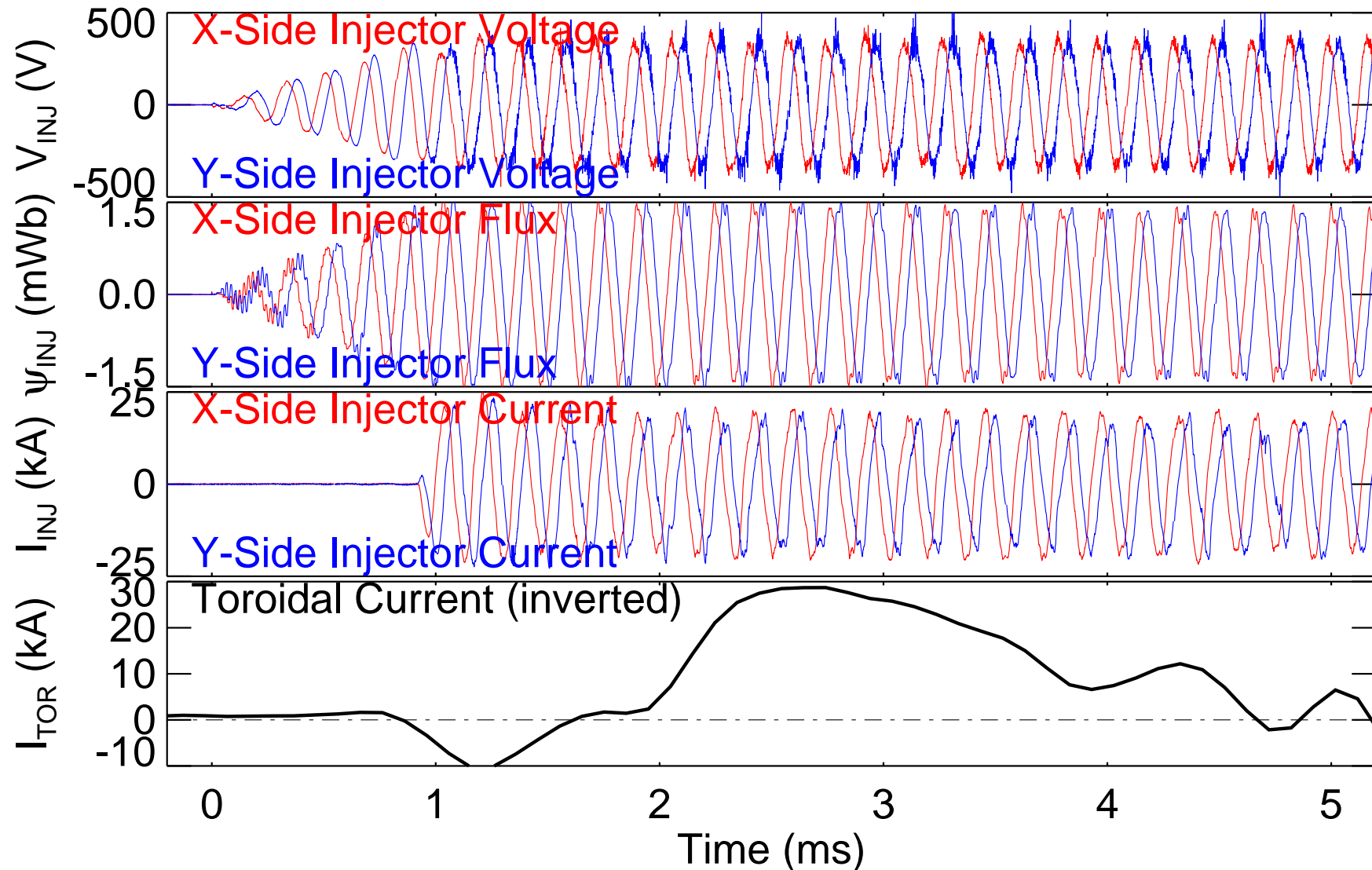
- The HIT–SI confinement region has a “bow-tie” shape for improved stability and high  $\beta$ .
- HIT–SI has two inductive helicity injectors, which allows constant rates of helicity and power injection.
- Like a rectifier, AC fields, voltages, and currents in HIT–SI can form and sustain a DC magnetized plasma.

## HIT–SI Diagnostic Locations



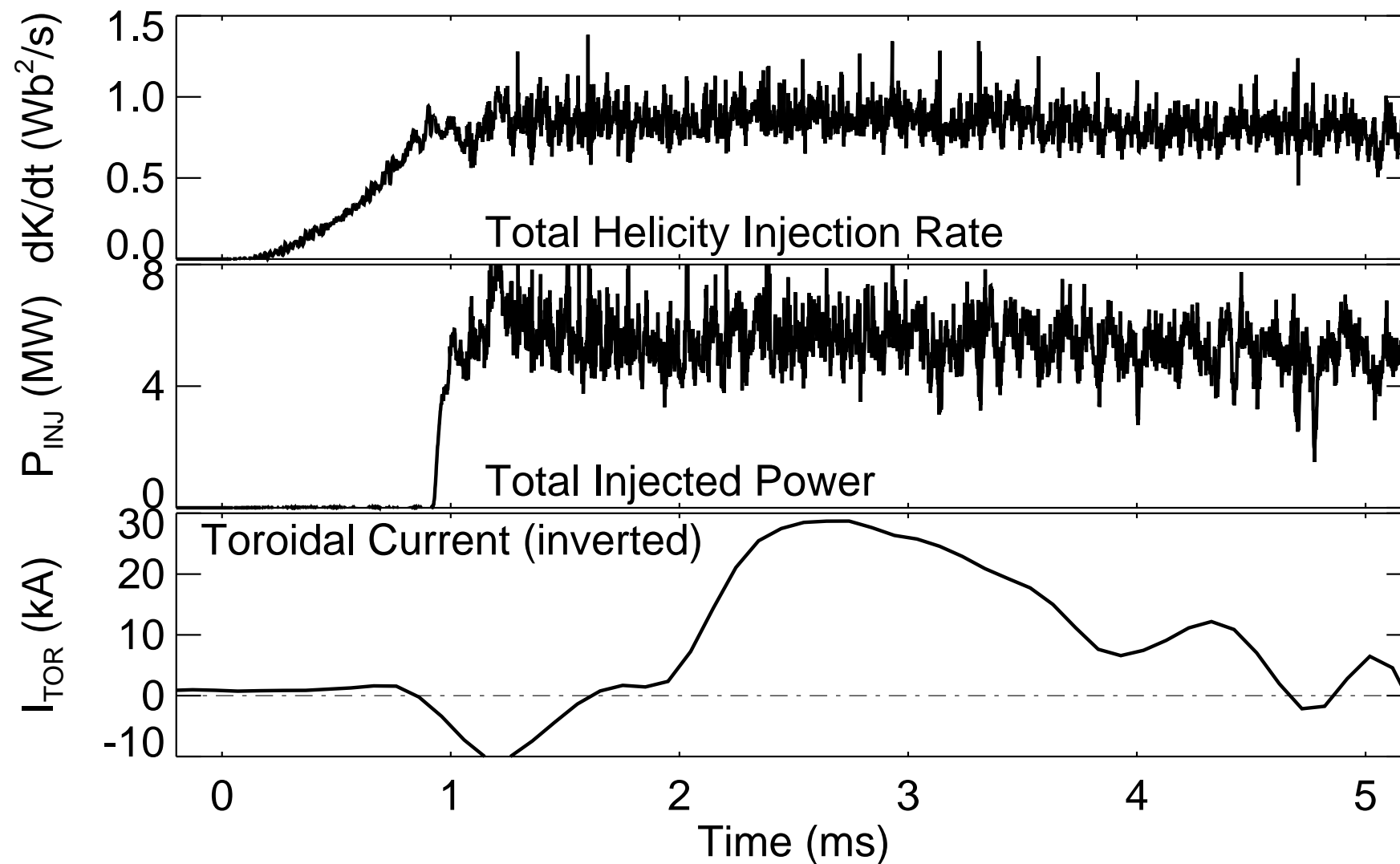
# Spheromak Formation with Toroidal Current of 29 kA

## High Current HIT-SI Shot #105914



# Spheromak Formation with Toroidal Current of 29 kA

## High Current HIT-SI Shot #105914



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

## HIT–SI Taylor-State Magnetic Equilibrium Model

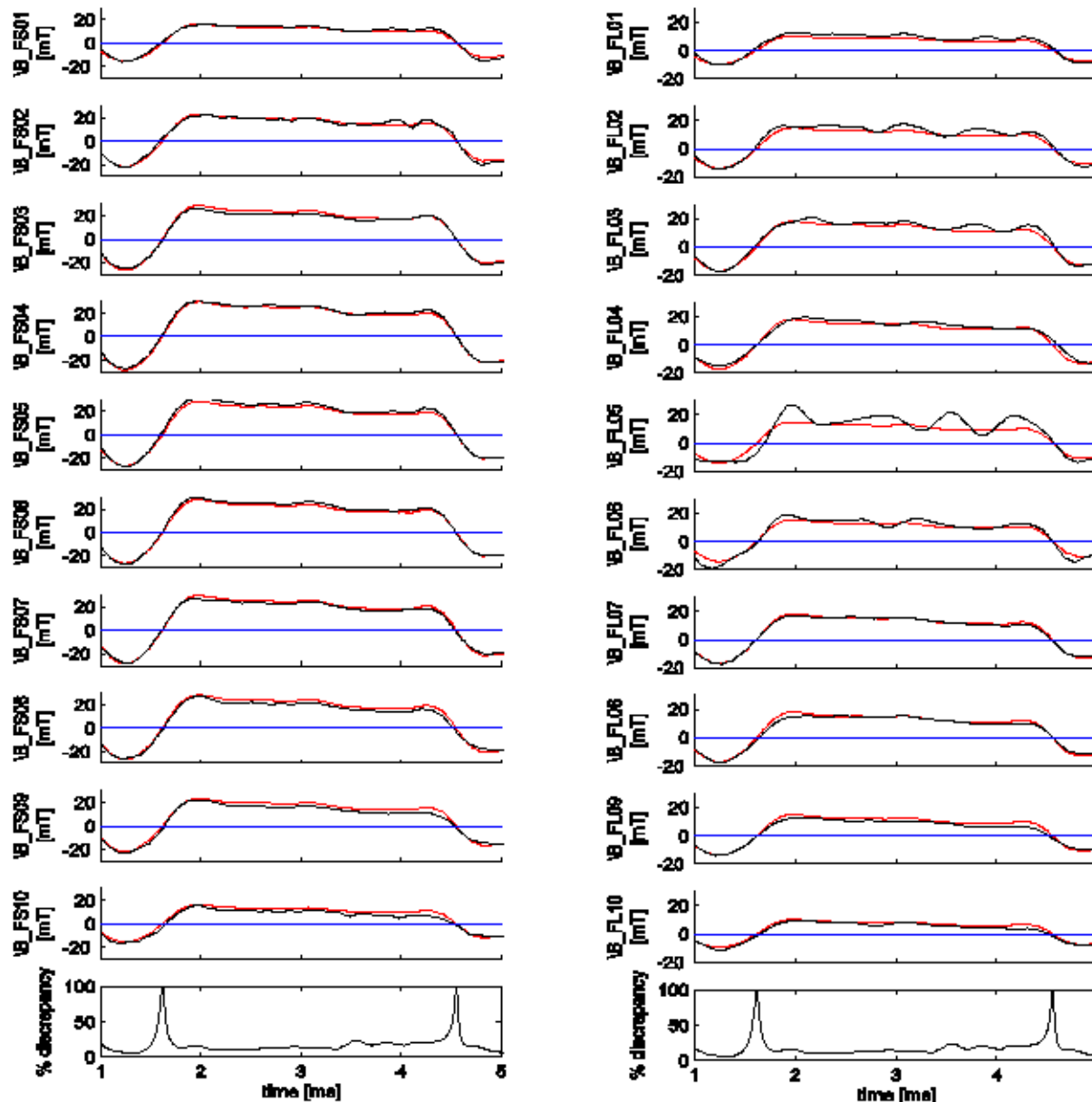
HIT–SI magnetic equilibrium model uses three basis functions  
(these Taylor-state basis functions are solutions to  $\nabla \times \mathbf{B} = \lambda \mathbf{B}$ )

(1) is the lowest-energy (spheromak) eigenstate (has  $\lambda=10.4 \text{ m}^{-1}$ ),  
scaled by the toroidal spheromak current  $I_{\text{TOR}}$ .

(2) and (3) are injector-driven basis functions (undetermined  $\lambda$ ),  
scaled by the measured current in each injector.

We choose  $\lambda=10.4 \text{ m}^{-1}$  for all three basis functions  
 $\Rightarrow$  Superposition is Taylor-State equilibrium.

# Axisymmetric $B_p$ vs. Scaled Spheromak Eigenfunction



Comparison to experiment:  
HIT-SI discharge #105278.

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

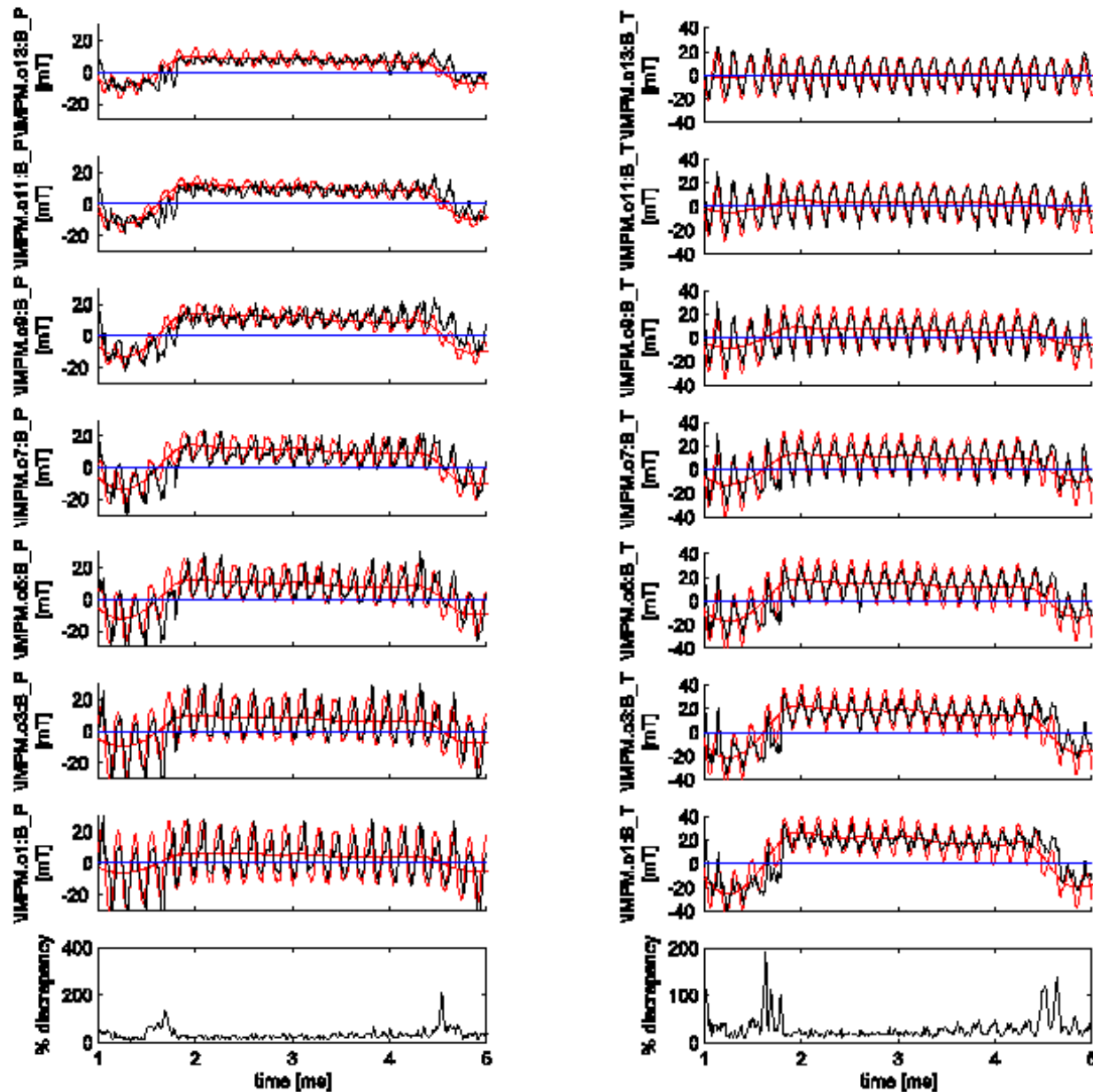
Black: experimental values  
Red: scaled Taylor model

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

# 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.

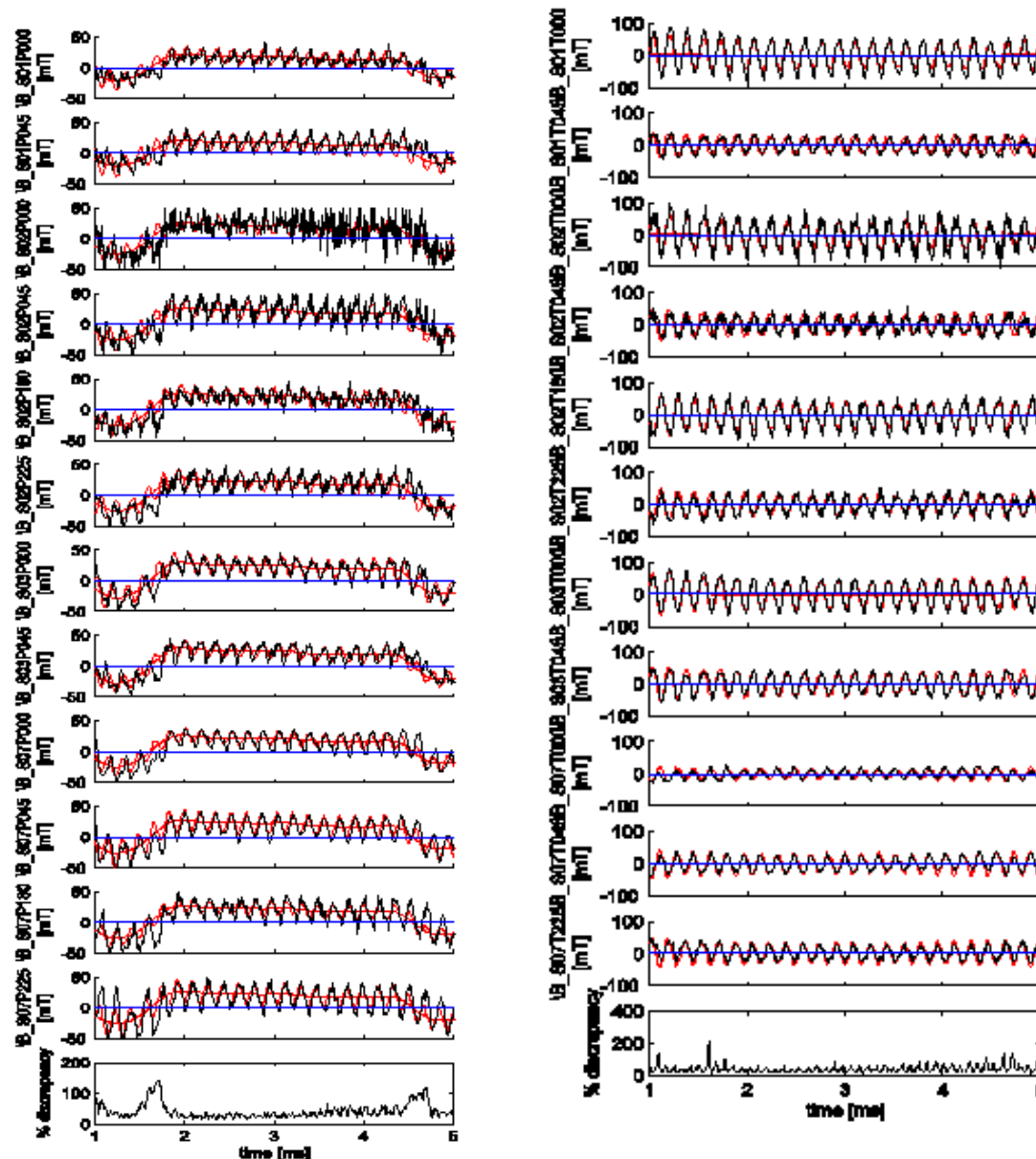
Bottom probe is deepest,  
at  $R=0.36$  m.  
Top probe is near edge,  
at  $R=0.52$  m.

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  $I_{\text{TOR}}$

See Paul E. Sieck, PhD dissertation, University of Washington, 2006.

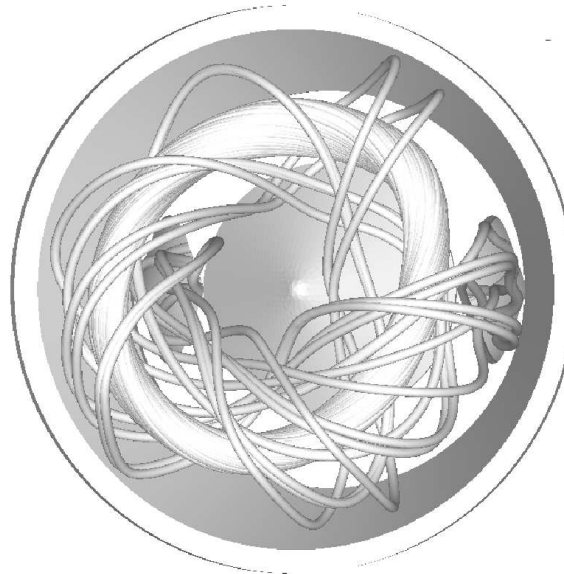
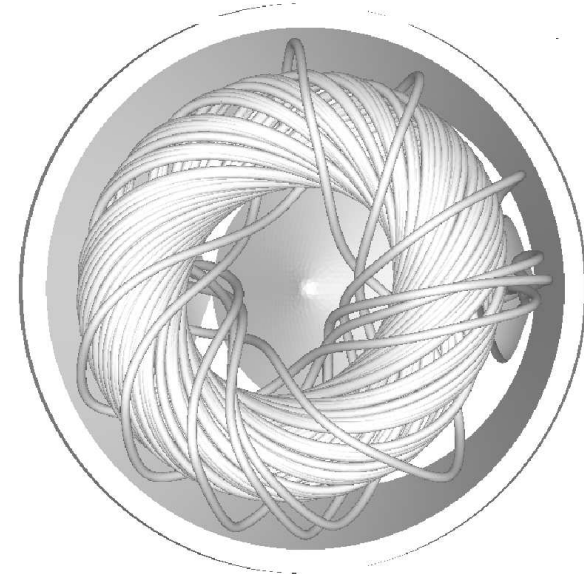
- Taylor-state model can also be used to trace field lines, for visualizing the equilibrium geometry.

## 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.*, Phys. Rev. Lett. **97**, 115003 (2006).

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

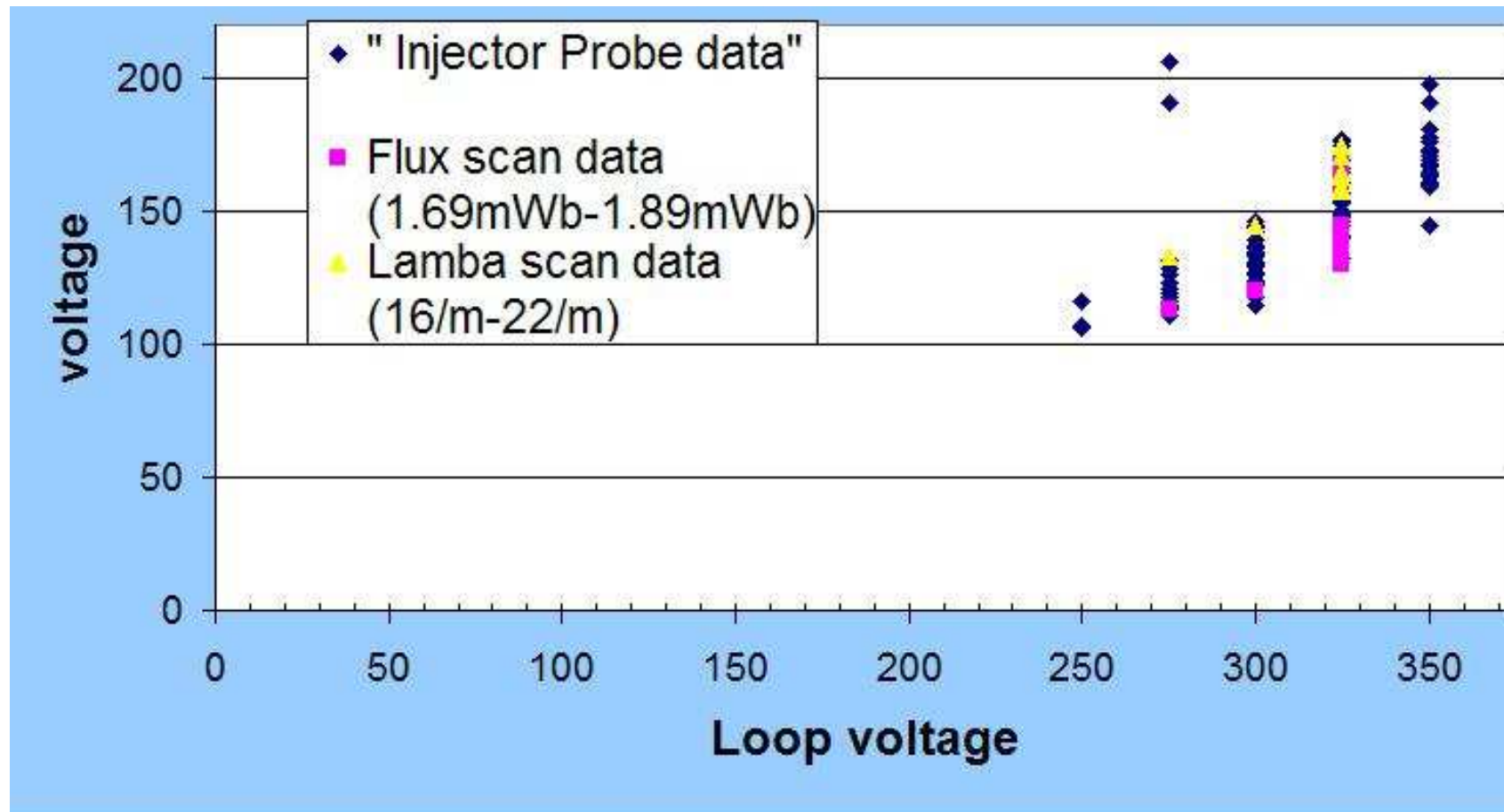
- Arrays of voltage probes are installed at the mouths of one HIT–SI helicity injector (the X-injector).
- These probes provide a direct measurement of the voltage drop within the confinement region.
- This measured voltage drop can then be compared to the total inductive loop voltage in the injector.

# 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

## Talk Summary

- Steady Inductive Helicity Injection (SIHI) can be used to drive current in any toroidal magnetized plasma.  
⇒ Simple, inexpensive, steady-state current sustainment.
- HIT–SI demonstrates that SIHI can form spheromaks
  - with  $I_{\text{TOR}} \leq 29$  kA,
  - with  $I_{\text{TOR}} = 1.5 \times I_{\text{INJ}}$ , and
  - using less than 6 MW of injected power.
- Spatial structure and temporal evolution of HIT–SI magnetic fields are well-described by a Taylor-state equilibrium model.  
Taylor-state model predicts separatrix formation at  $I_{\text{TOR}} \approx I_{\text{INJ}}$ .
- Internal electric field measurements show that the injector voltages extend into the confinement region, and drive the spheromak.

## Near-Term HIT–SI Plans

- **HIT–SI is presently in an outage period**
- **HIT–SI Device Repairs and Upgrades:**
  - Repair of particular interior surfaces, including the alumina plasma-facing surface
  - Upgrade of injector flux capability
  - Inter-shell current bridges
  - Repair of multichord H-alpha diagnostic
  - Preliminary work for active flux conserver
  - New turbopump and vacuum system controls
- **Plan to resume operations in mid 2007**
  - Higher injector voltage and flux
  - Cleaner, hotter plasmas

Electronic version of this talk (in PDF) is available at:

<http://plasma.aa.washington.edu/redd/>

Other presentations and manuscripts are also available.

Recent HIT–SI and SIHI-related publications:

- Jarboe *et al.*, Phys. Rev. Lett. **97**, 115003 (2006).
- Sieck *et al.*, Nucl. Fusion **46**, 254 (2006).
- Sieck *et al.*, IEEE Trans. Plasma Sci. **33**, 723–728 (2005).
- Izzo and Jarboe, Phys. Plasmas **12**, 056109 (2005).
- Shumlak and Jarboe, Phys. Plasmas **7**, 2959 (2000).
- Jarboe, Fusion Technology **36**, 85 (1999).

Recent HIT–II and NSTX CHI-related publications:

- Raman *et al.*, Phys. Plasmas **14**, 022504 (2007).
- Redd *et al.*, IEE Japan Trans. Fundamentals Mat. **125**, 887 (2005).
- O’Neill *et al.*, Phys. Plasmas **12**, 122506 (2005).
- Mueller *et al.*, Phys. Plasmas **12**, 070702 (2005).
- Raman *et al.*, Phys. Plasmas **11**, 2565 (2004).