HIT - SI

Status and Recent Upgrades on the HIT-SI Spheromak Experiment

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Helicity Injected Torus (HIT) Program
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Outline

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- Steady Inductive Helicity Injection (SIHI)
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  - » Operation

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- Conclusions

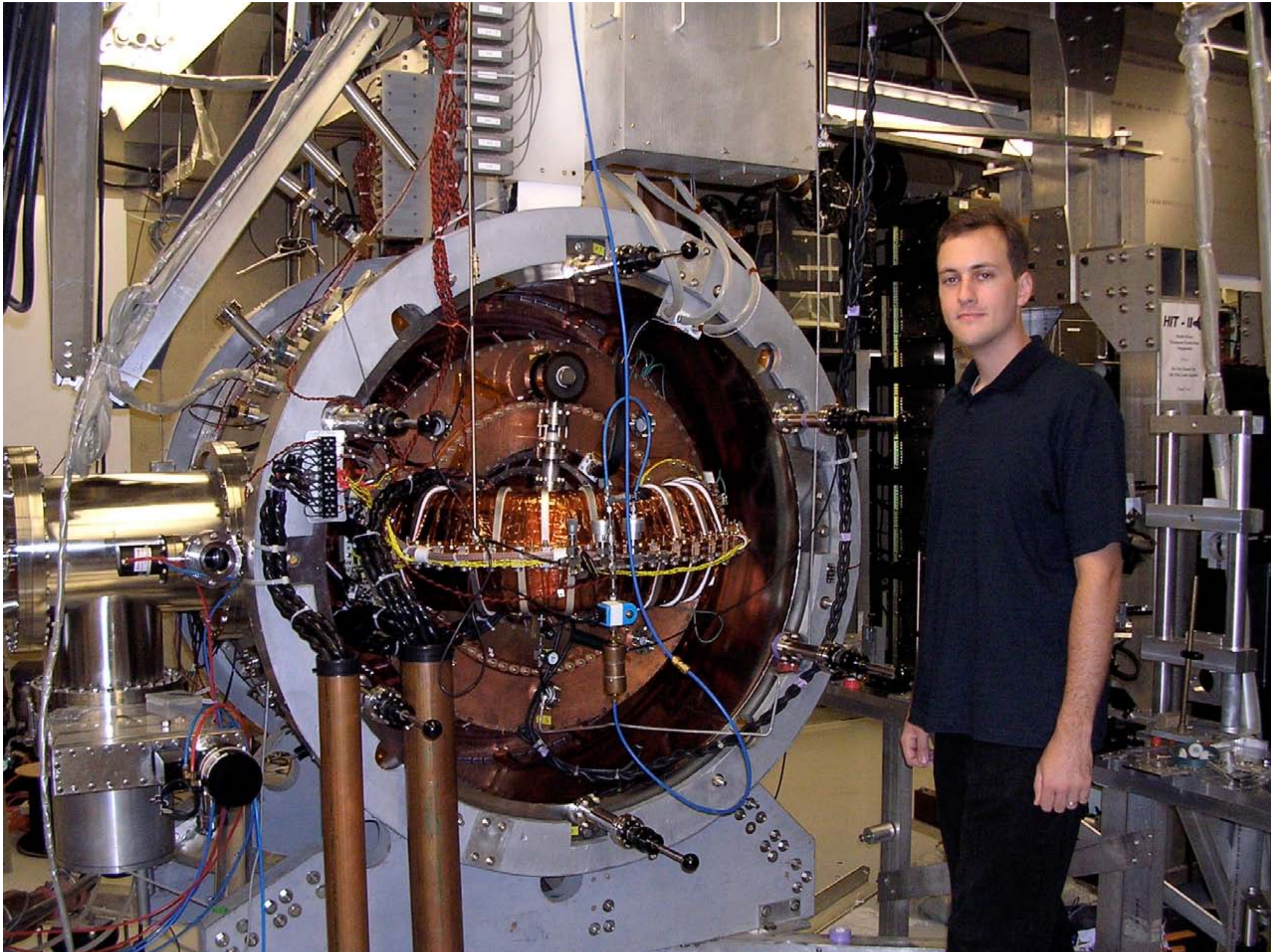
Motivation

Critical issues for spheromaks include current drive, operation at high β, and confinement.

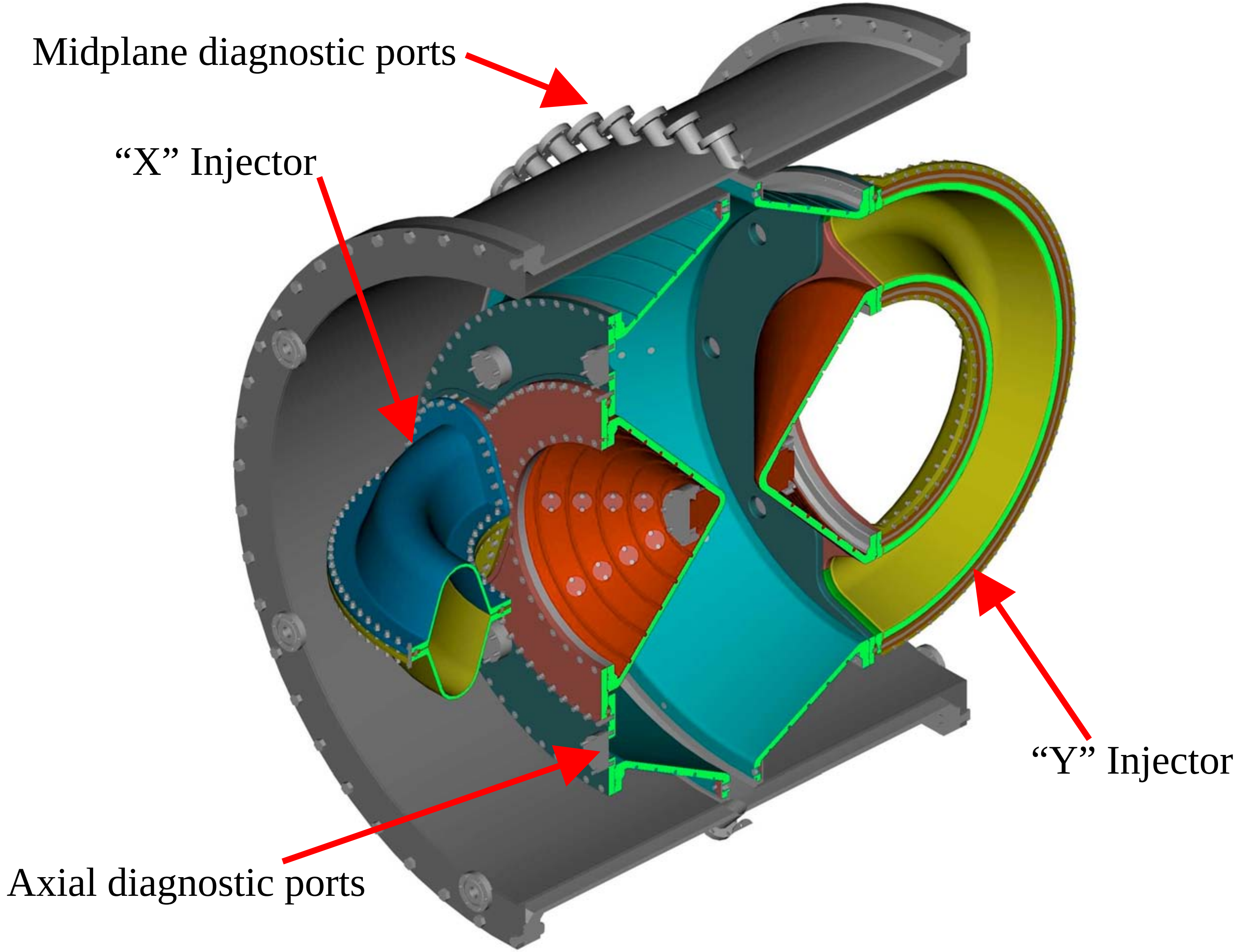
The Helicity Injected Torus with Steady Inductive Helicity Injection (HIT-SI) addresses all these issues:

- Steady-state inductive operation, providing near-constant helicity injection rate and power input
- High β provided by shape and current profile
- Minimal plasma-wall interaction
- Injected power always flows into the plasma

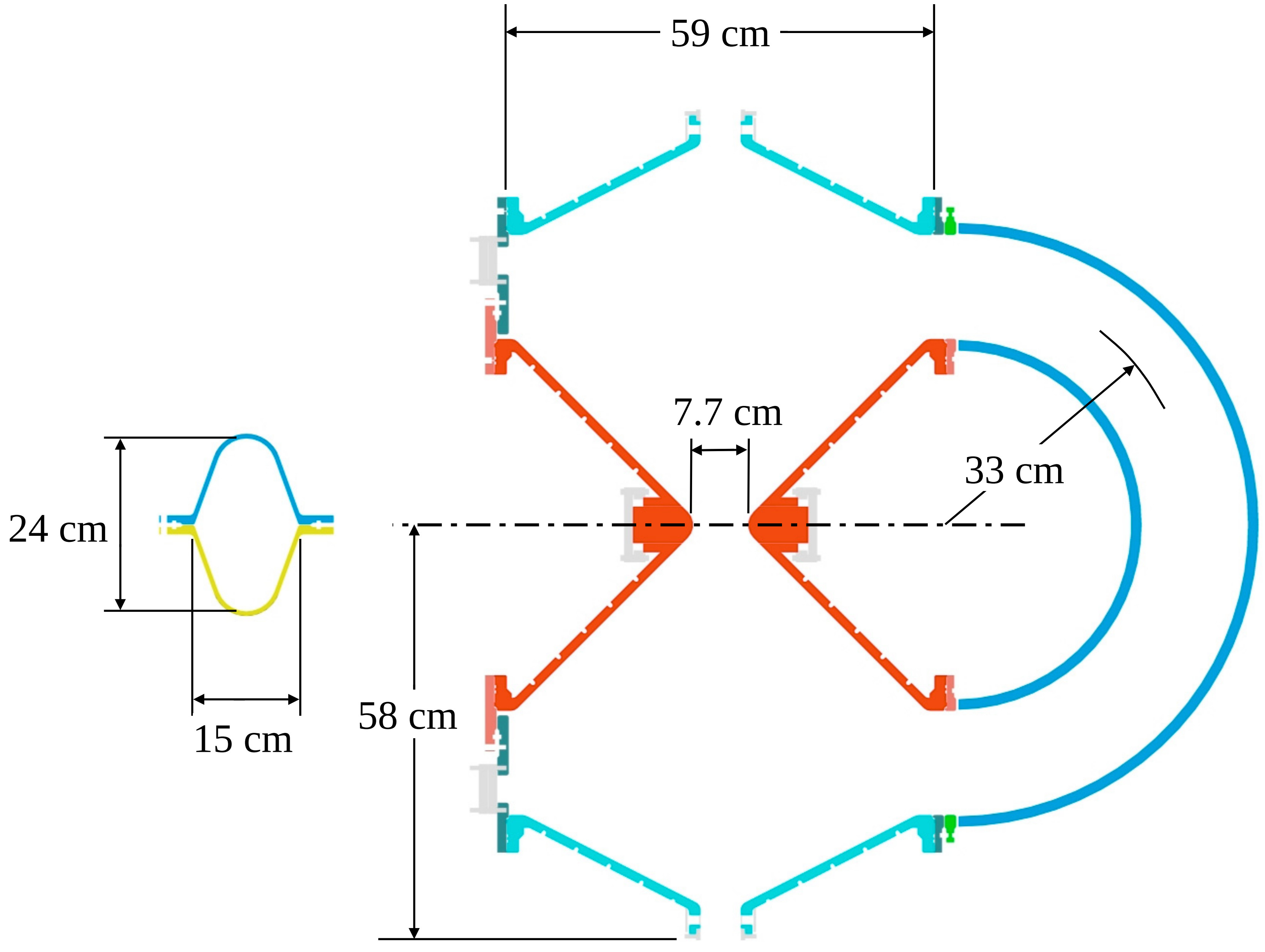
The HIT-SI Device



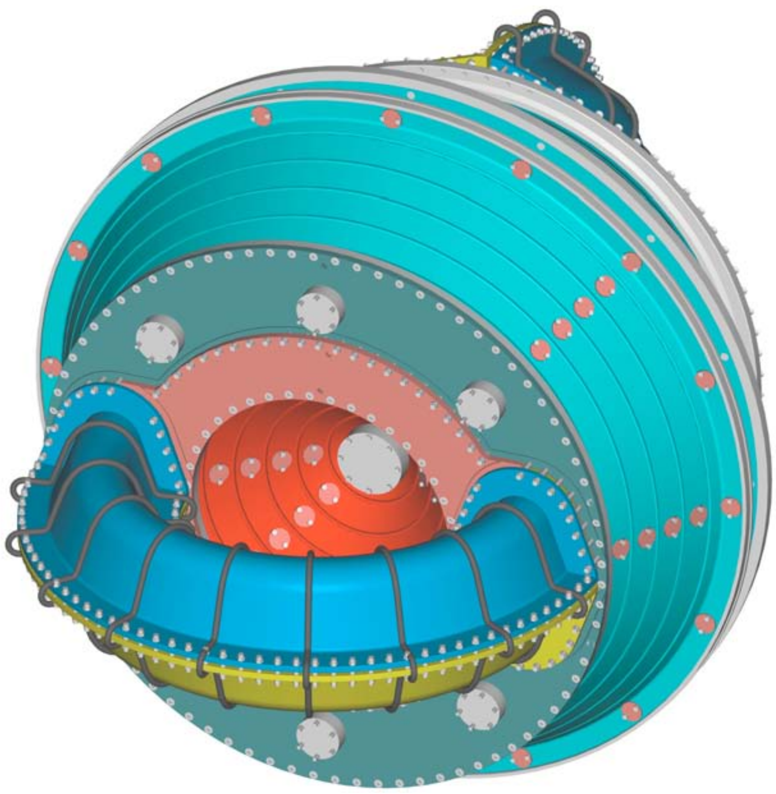
A “Cutaway” View of the HIT-SI Device



HIT-SI Dimensions

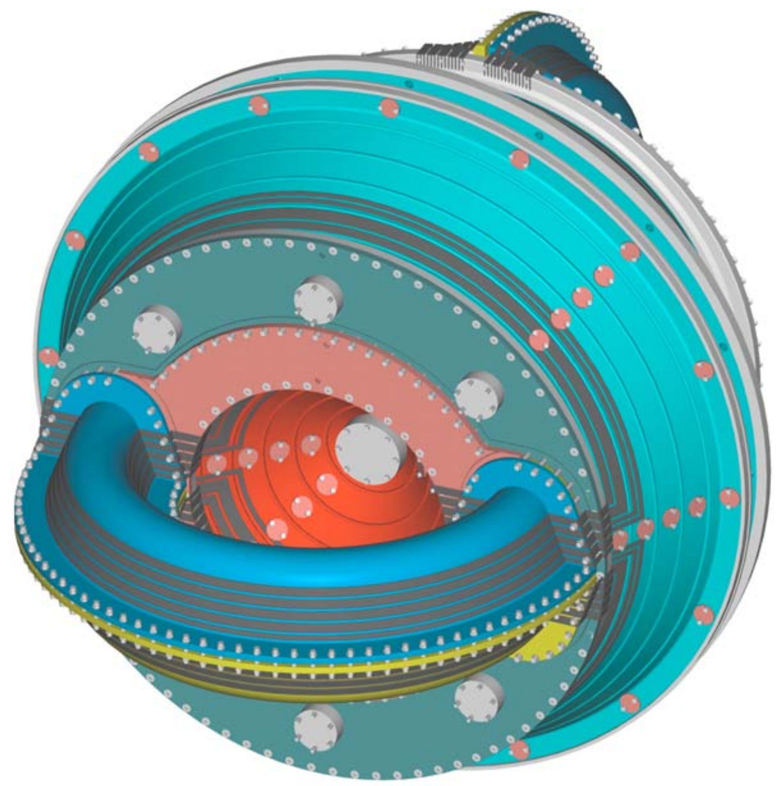


Each Injector Requires Two Coil Sets



Flux Coil

Creates a “toroidal” field in the injector.



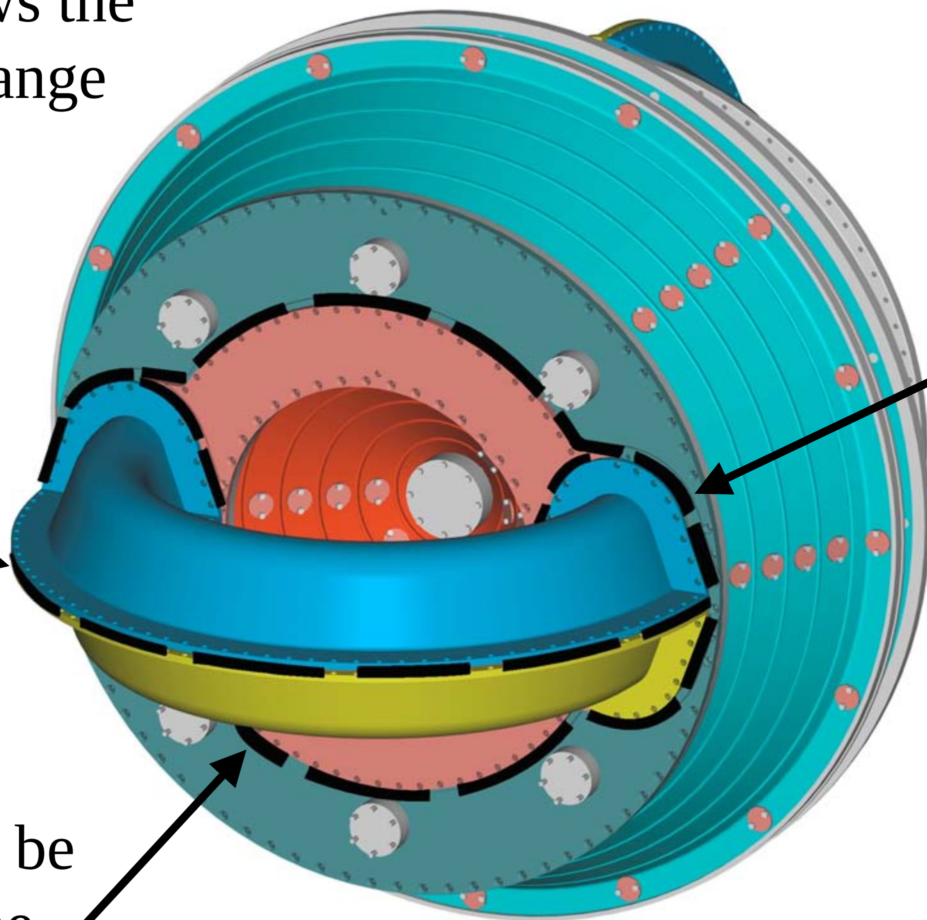
Voltage Coil

An “air core” transformer that applies a loop voltage to the injector plasma.

The Coils Require Insulating Gaps in the Shell

Toroidal gap allows the injector flux to change

Poloidal gaps prevent shorting of the injector loop voltage



Toroidal gap must be continued along the equilibrium flux conserver

Steady Inductive Helicity Injection (SIHI) - Concept

The helicity injection rate is

$$\dot{K}_{inj} = 2\,V_{inj}\psi_{inj}$$

where V_{inj} is the injector loop voltage and ψ_{inj} is the injector flux.

In the case of SIHI, $V_{inj} = -\dot{\varphi}_{transformer}$.

If V_{inj} and ψ_{inj} are varied sinusoidally and in phase, then

$$\dot{K}_{inj} = 2V_0\psi_0 \sin^2 \omega t$$

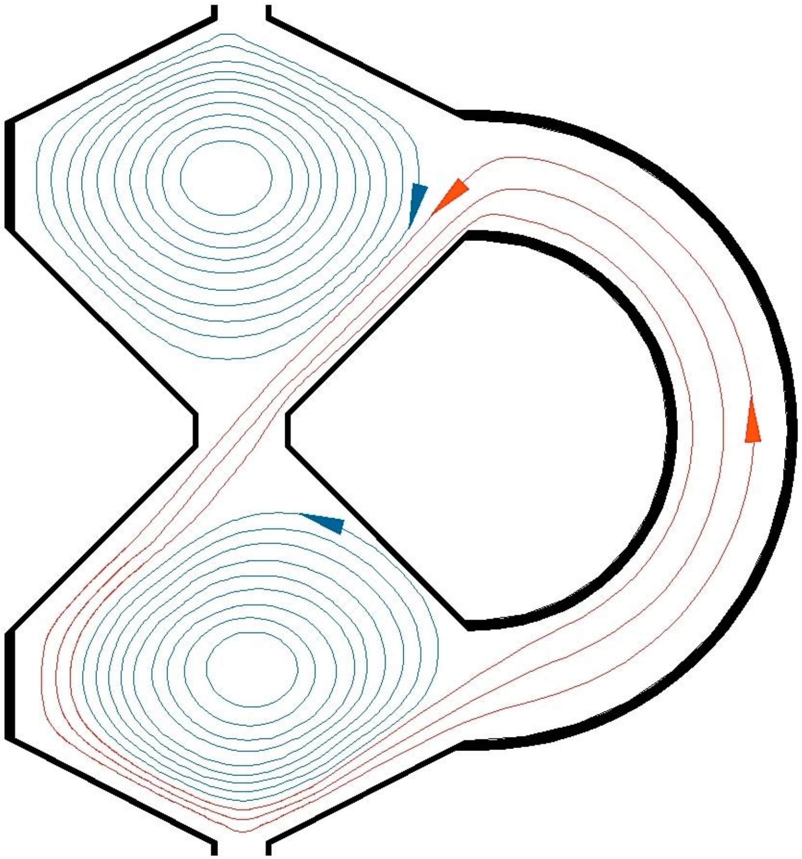
Add a second injector operating 90° out of phase:

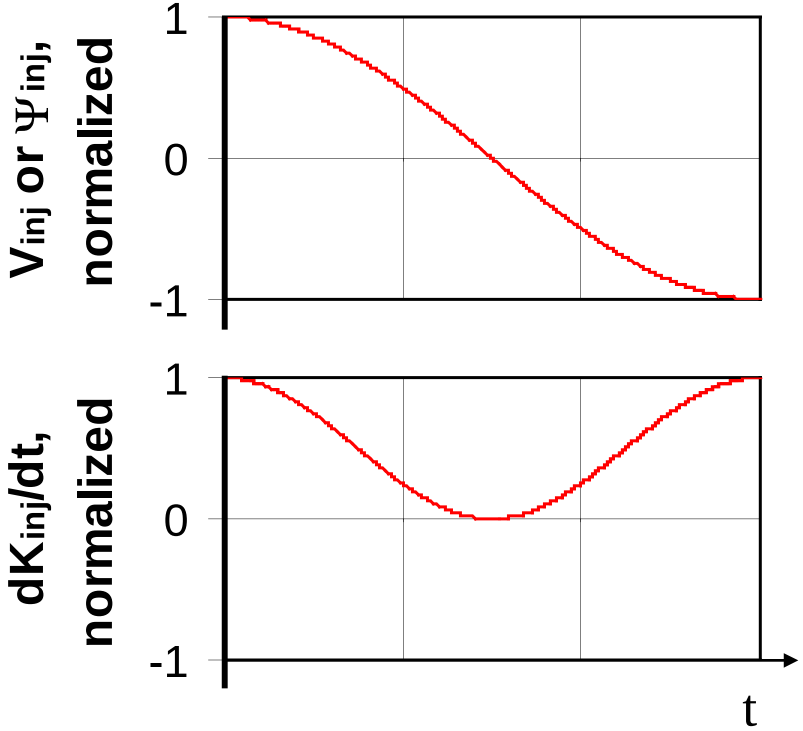
$$\dot{K}_{inj} = 2V_0\psi_0 \sin^2 \omega t + 2V_0\psi_0 \cos^2 \omega t$$

$$= 2V_0\psi_0 \quad \rightarrow \quad \text{constant helicity injection rate}$$

Steady Inductive Helicity Injection (SIHI) - Operation

ωt=0

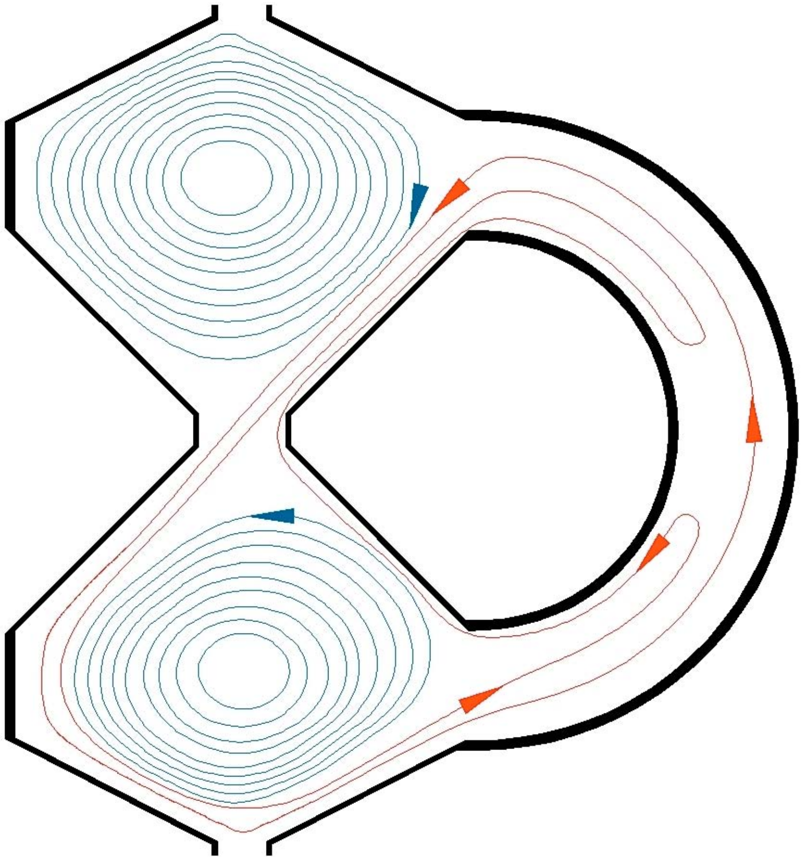


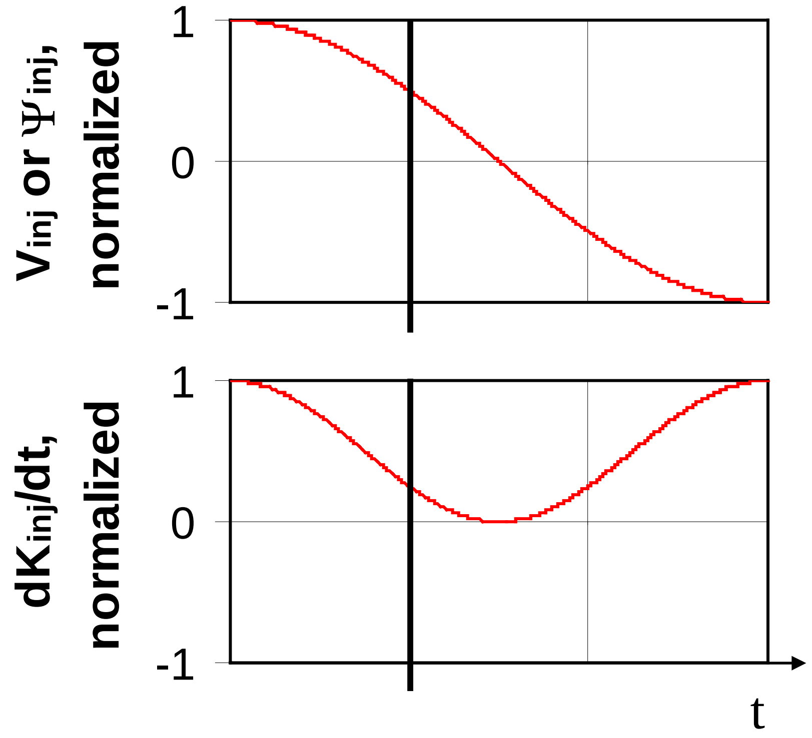


Injector flux, loop voltage, and plasma current at positive peak value

Steady Inductive Helicity Injection (SIHI) - Operation

$\omega t=\pi/3$

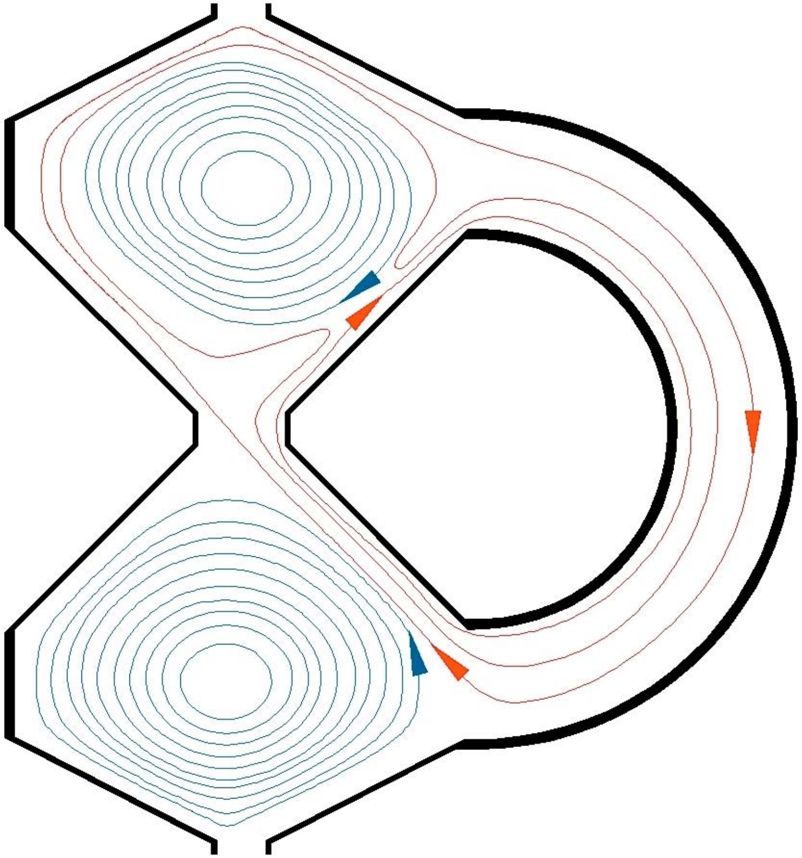


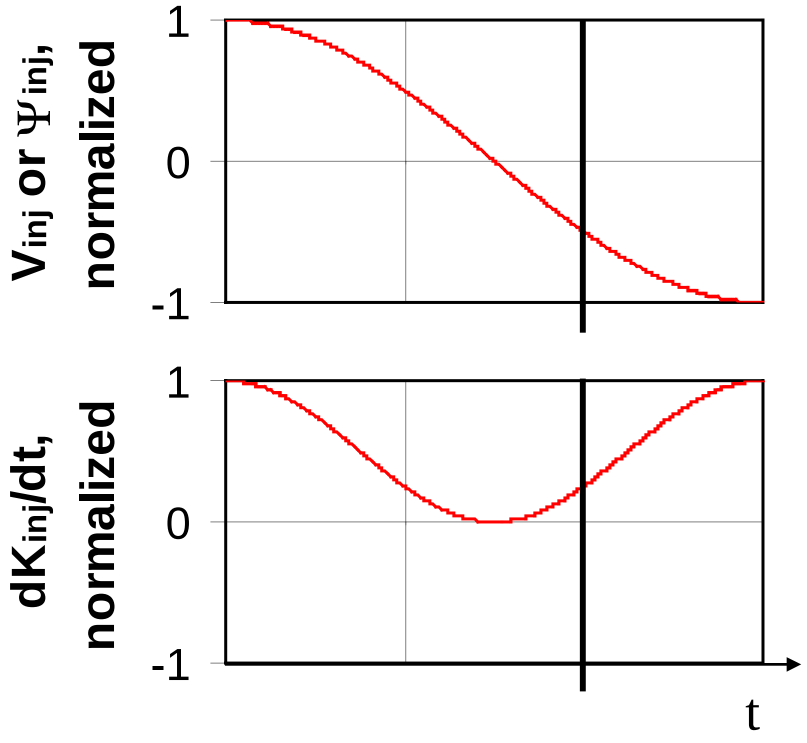


Injector flux is reduced by introducing negative field at the injector edge

Steady Inductive Helicity Injection (SIHI) - Operation

$\omega t = 2\pi/3$

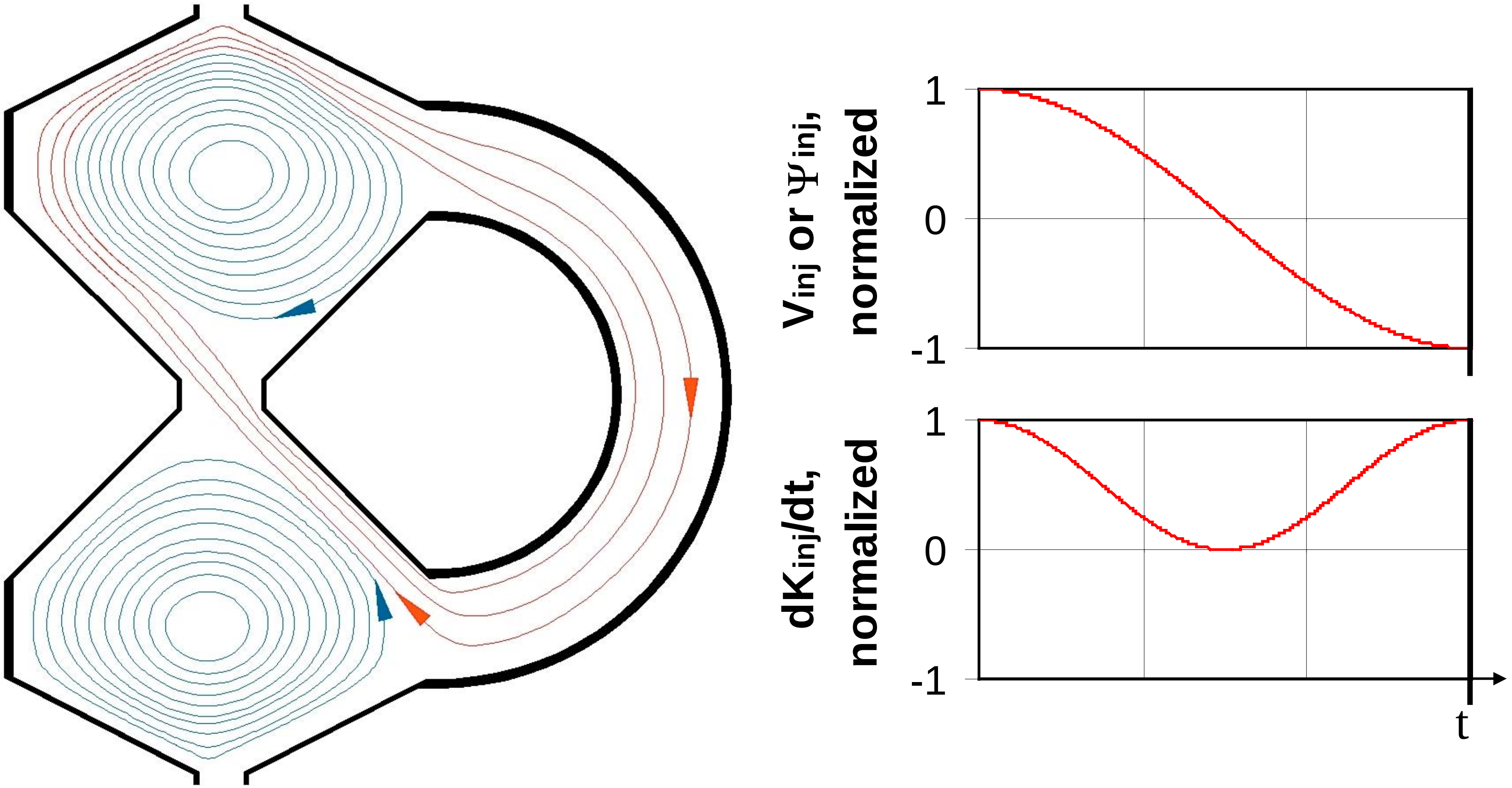




Past the zero crossing, the injector fields are assumed to reconnect with the oppositely-directed edge fields of the spheromak equilibrium

Steady Inductive Helicity Injection (SIHI) - Operation

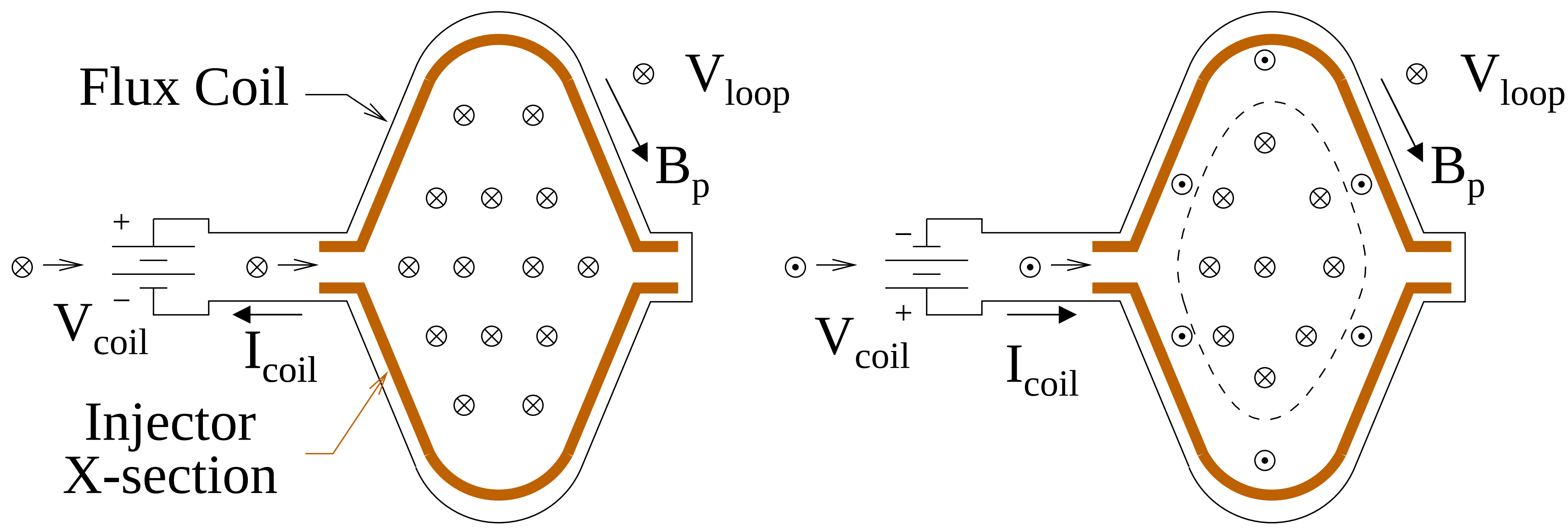
$\omega t = \pi$



Injector flux, loop voltage, and plasma current at negative peak value

Injector Acts as a Stabilized Pinch During Flux Buildup, and as an RFP During Flux Reduction

Always have $I_{coil}V_{coil} \geq 0$



During flux buildup

$\lambda_{inj} < \lambda_0$, stabilized pinch

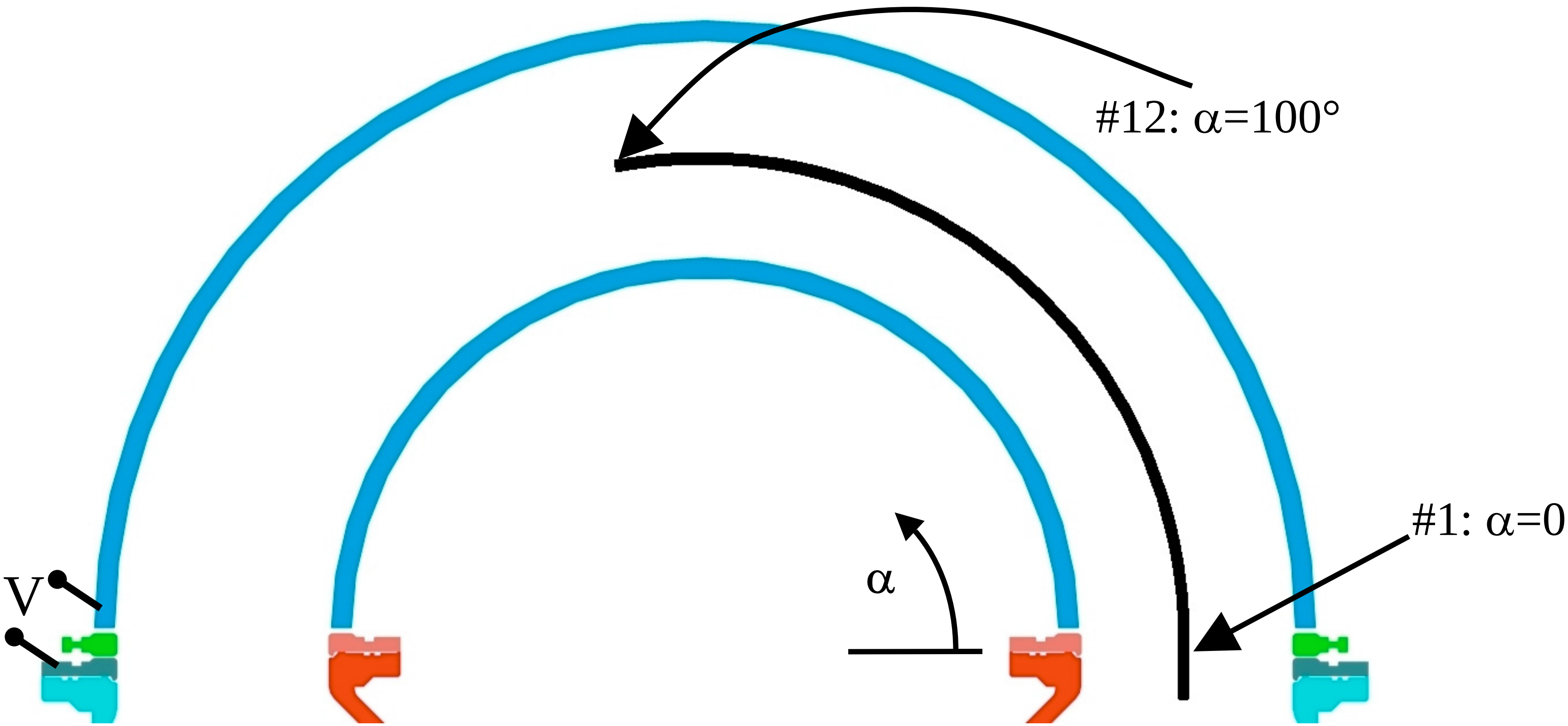
During flux reduction

$\lambda_{inj} > \lambda_0$, RFP

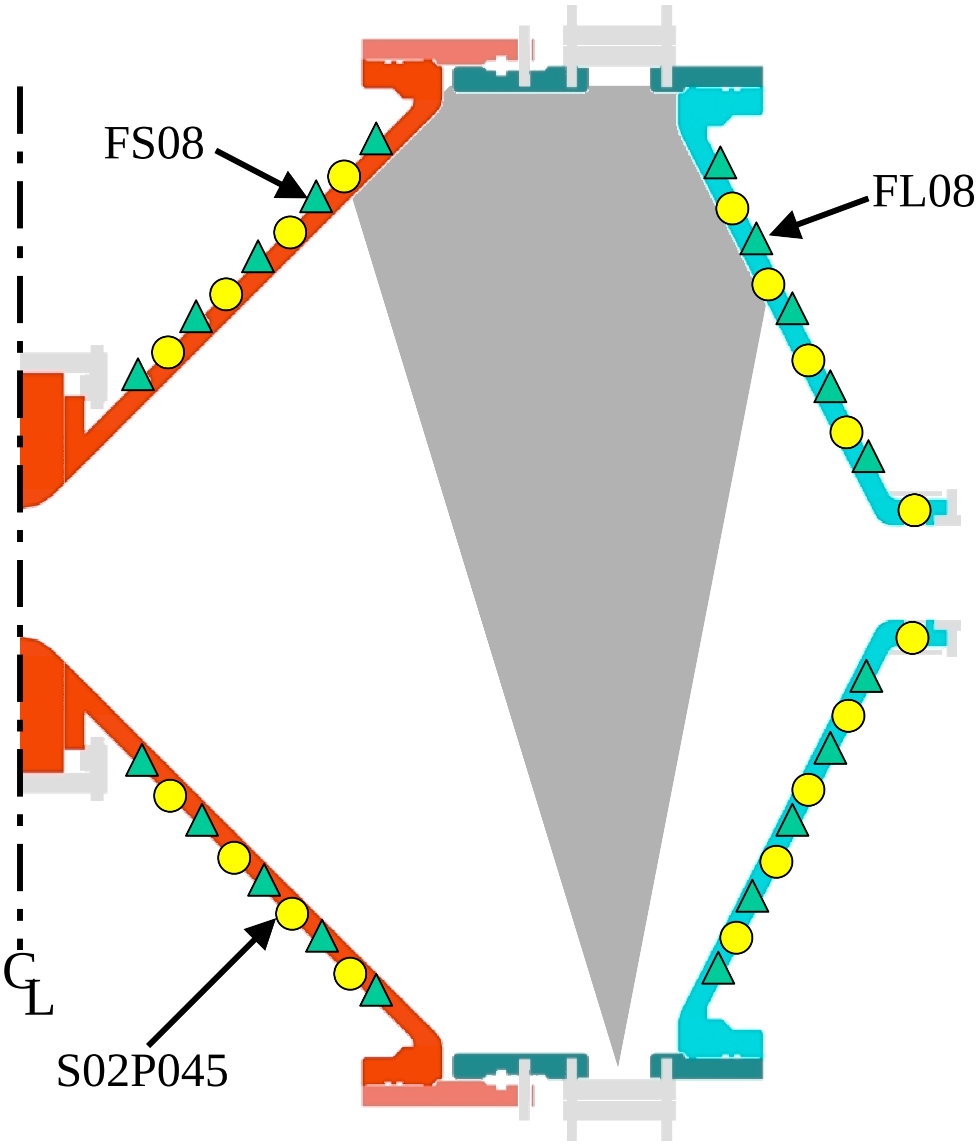
λ_0 is the eigenvalue for the injector such that B_t=0 at the wall

Injector Diagnostics

- Loop voltage (resistive divider)
- Flux loop
- Plasma current Rogowski loop
- 12-position, 3-axis internal magnetic field probe array



Equilibrium Region Diagnostics



20 flux loops

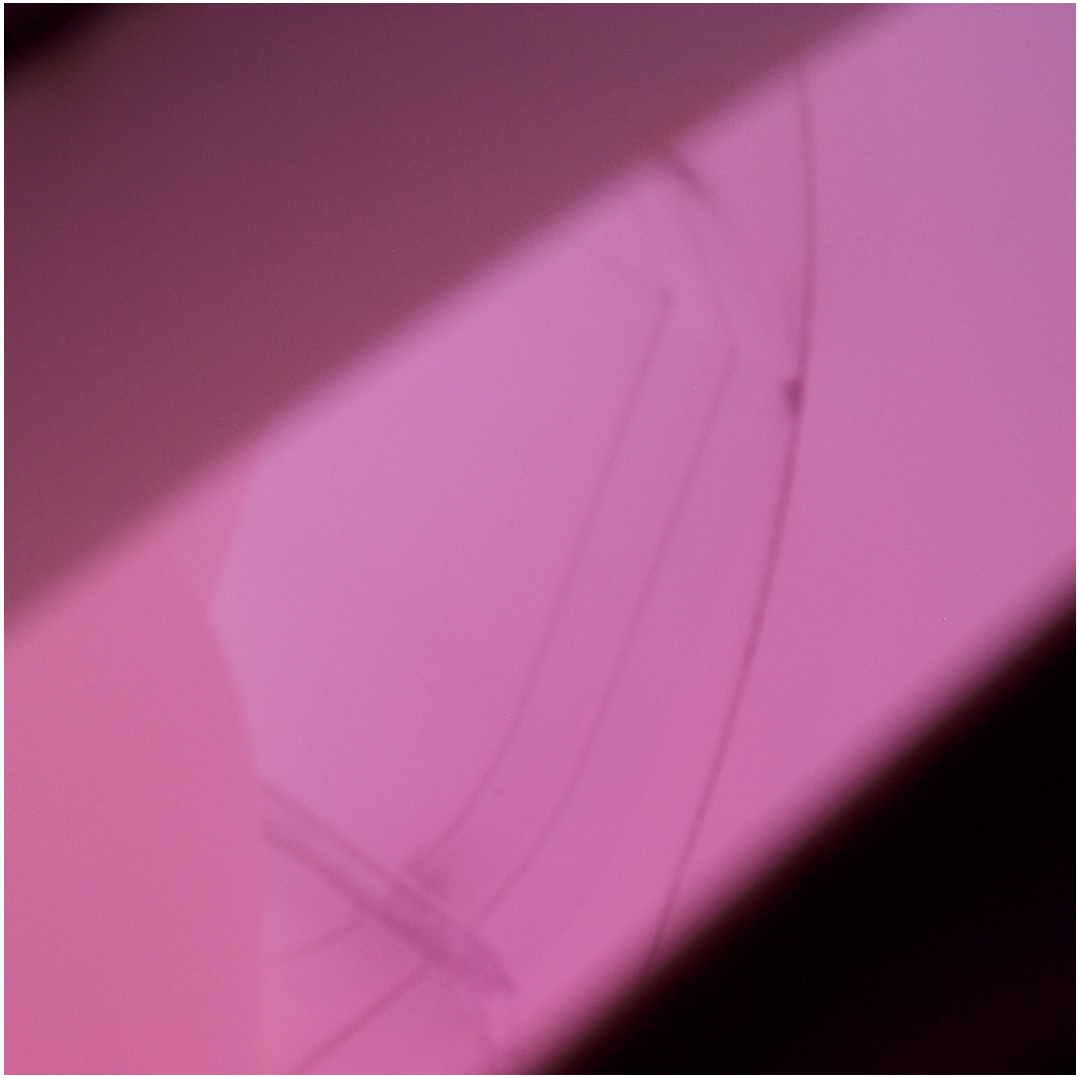
96 three-axis surface magnetic field probes

Shaded field of view:

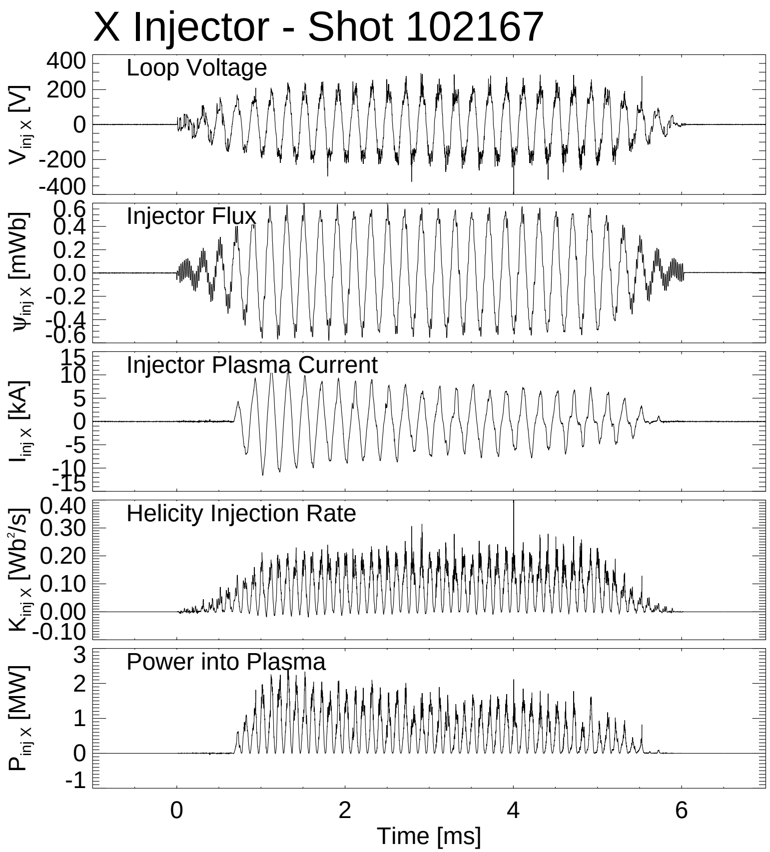
- H_{α} line radiation sensor
- Digital camera

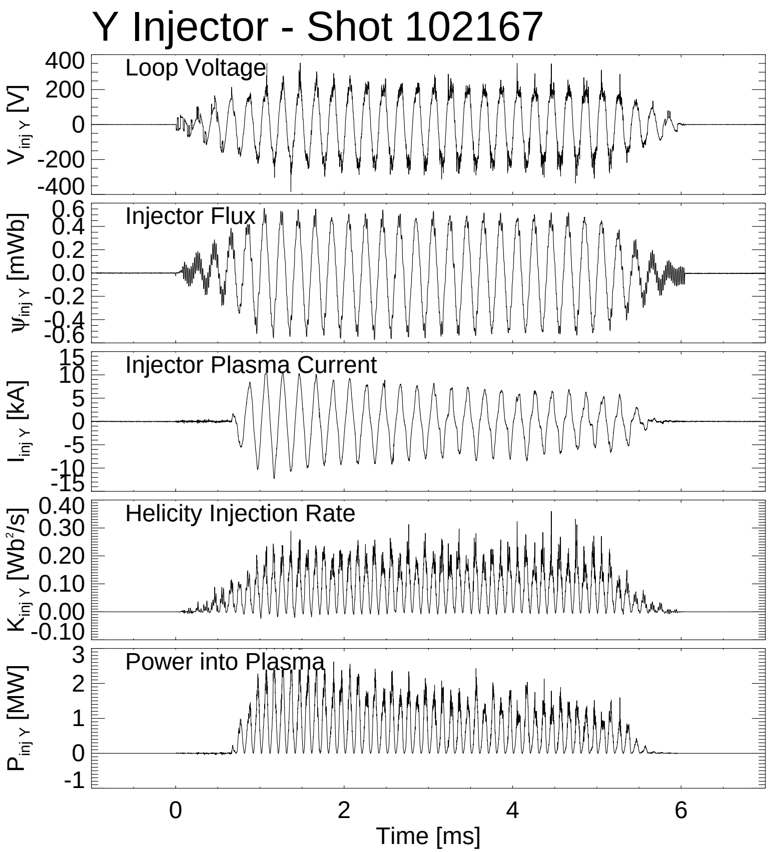
Image of HIT-SI Discharge

Shot #102167

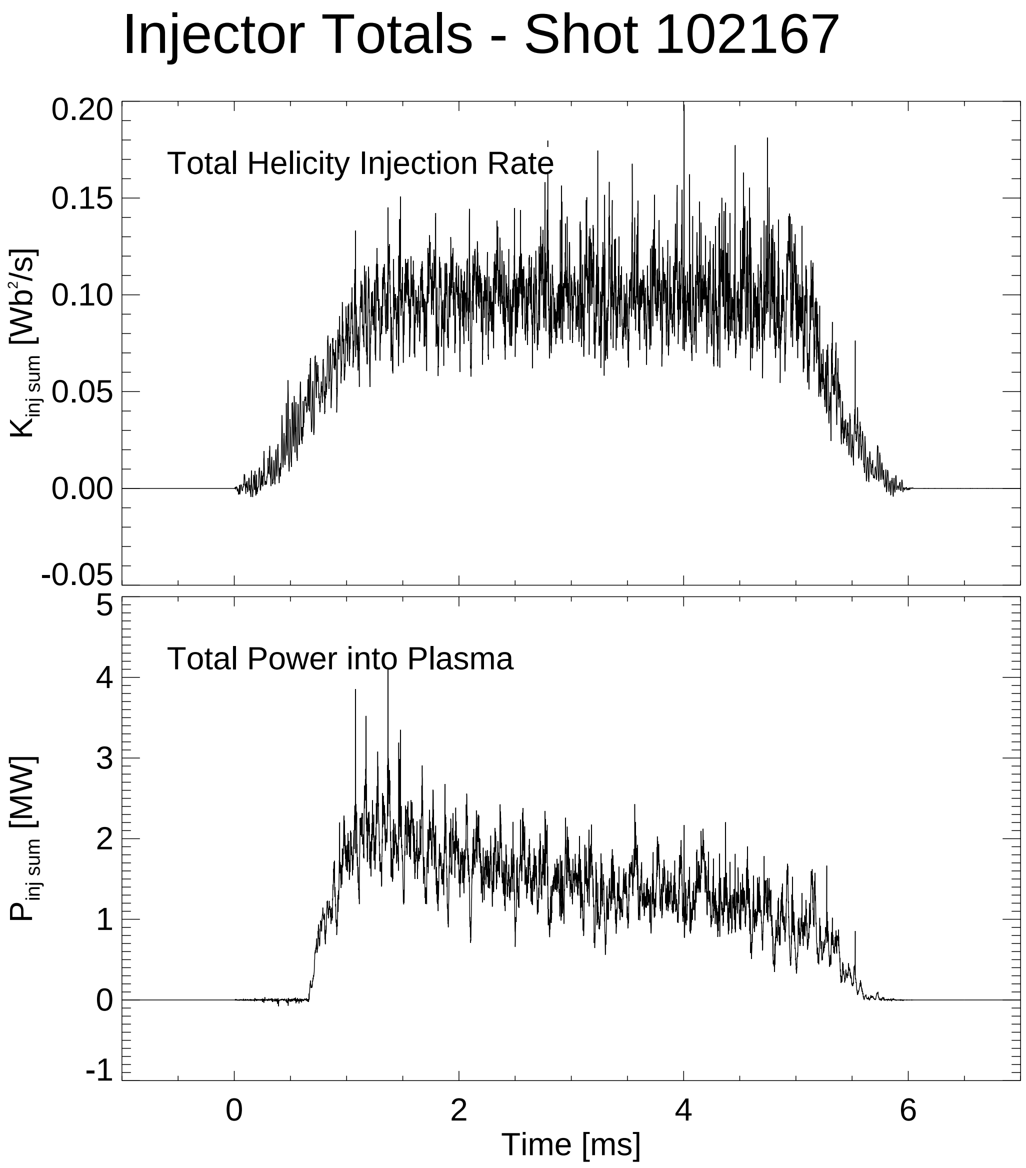


Parallel Operation of Injectors



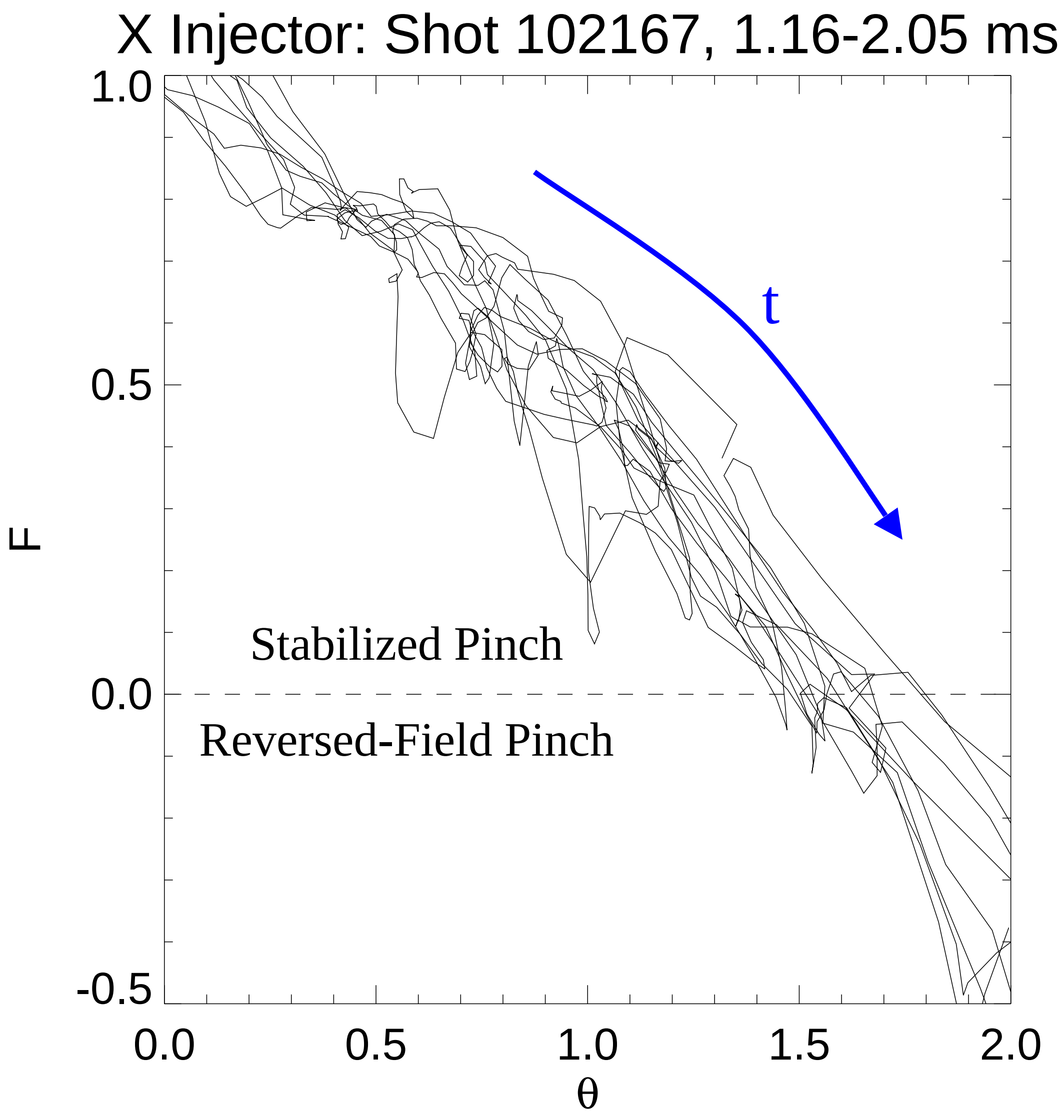


The Sustainment Parameters Add in Quadrature



- Global helicity injection rate is positive definite.
- Nearly-constant helicity injection rate and power input are achieved.
- Drop in input power is due to decrease in plasma current.

The Injectors Transition From Stabilized Pinches to RFPs



pinch parameter:

$$\theta \equiv \frac{B_\theta(a)}{\langle B_\phi \rangle} = \frac{\mu_0 I}{2\phi}\sqrt{\frac{A}{\pi}}$$

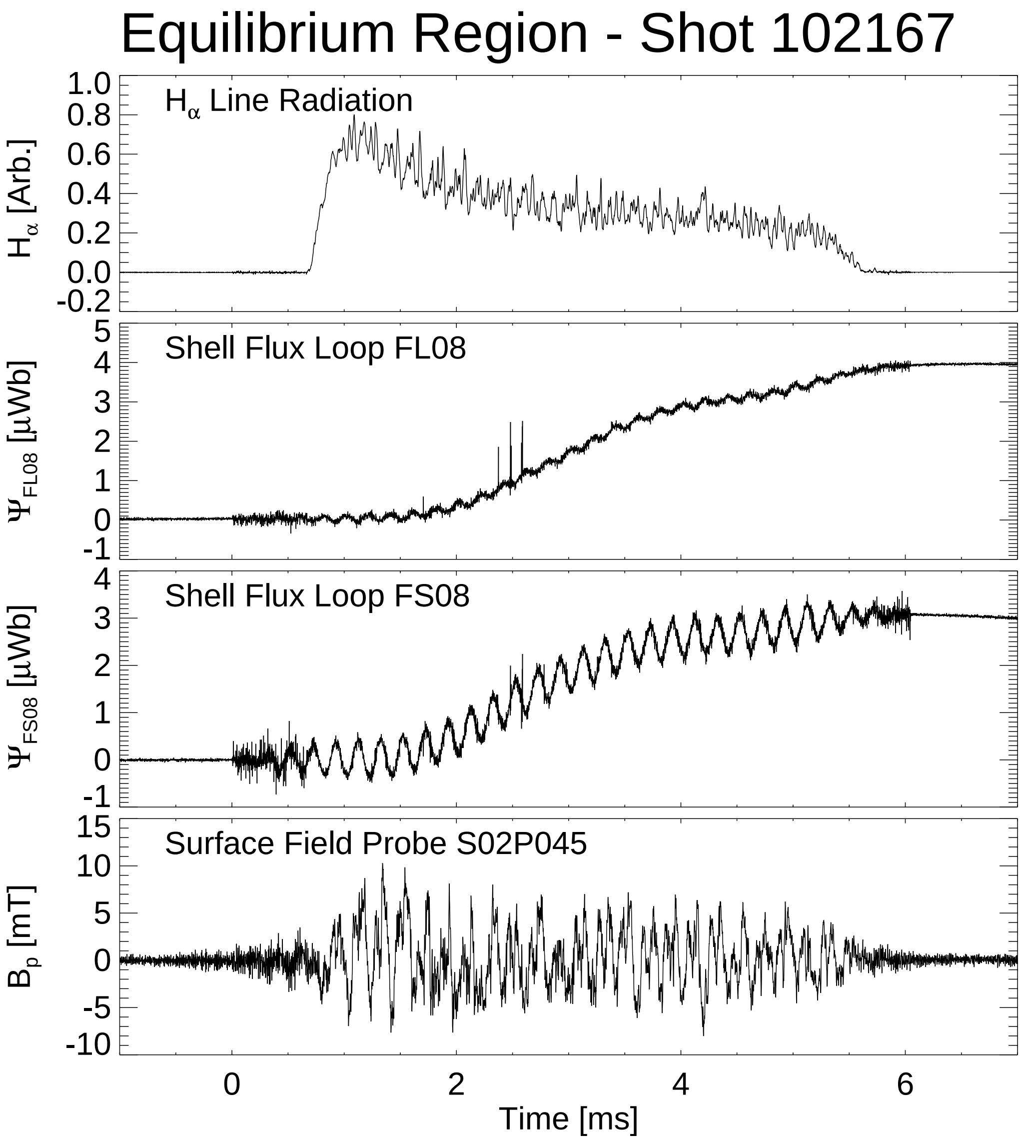
field reversal parameter:

$$F \equiv \frac{B_\phi(a)}{\langle B_\phi \rangle} = \frac{B_\phi(a)\,A}{\psi_{inj}}$$

where A is the cross-sectional area (239 cm^2).

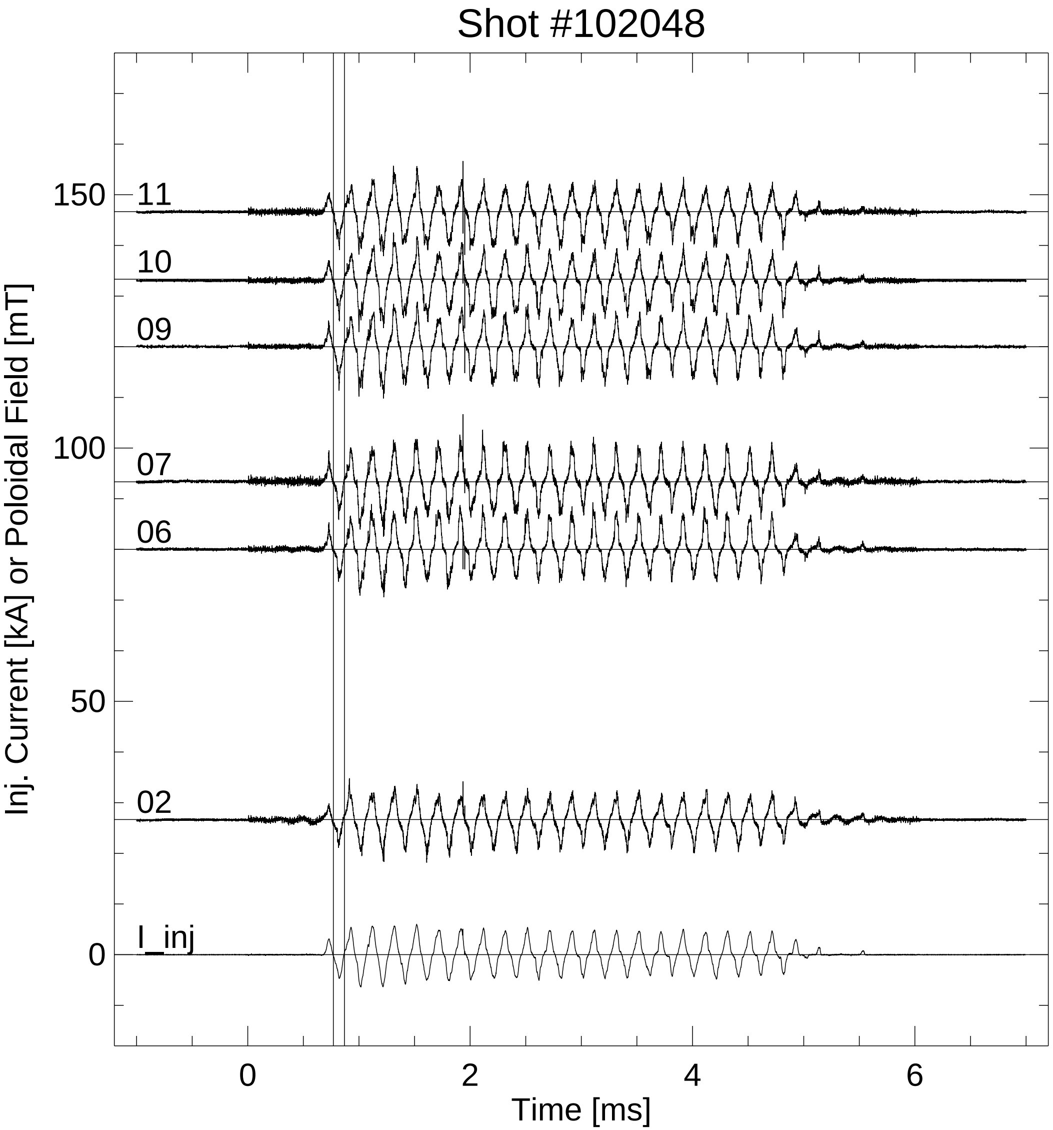
Field reversal at the wall (F<0) is expected to occur at $\theta > 1.2$ in circular RFPs at large aspect ratio.

Some Signs of Spheromak Formation



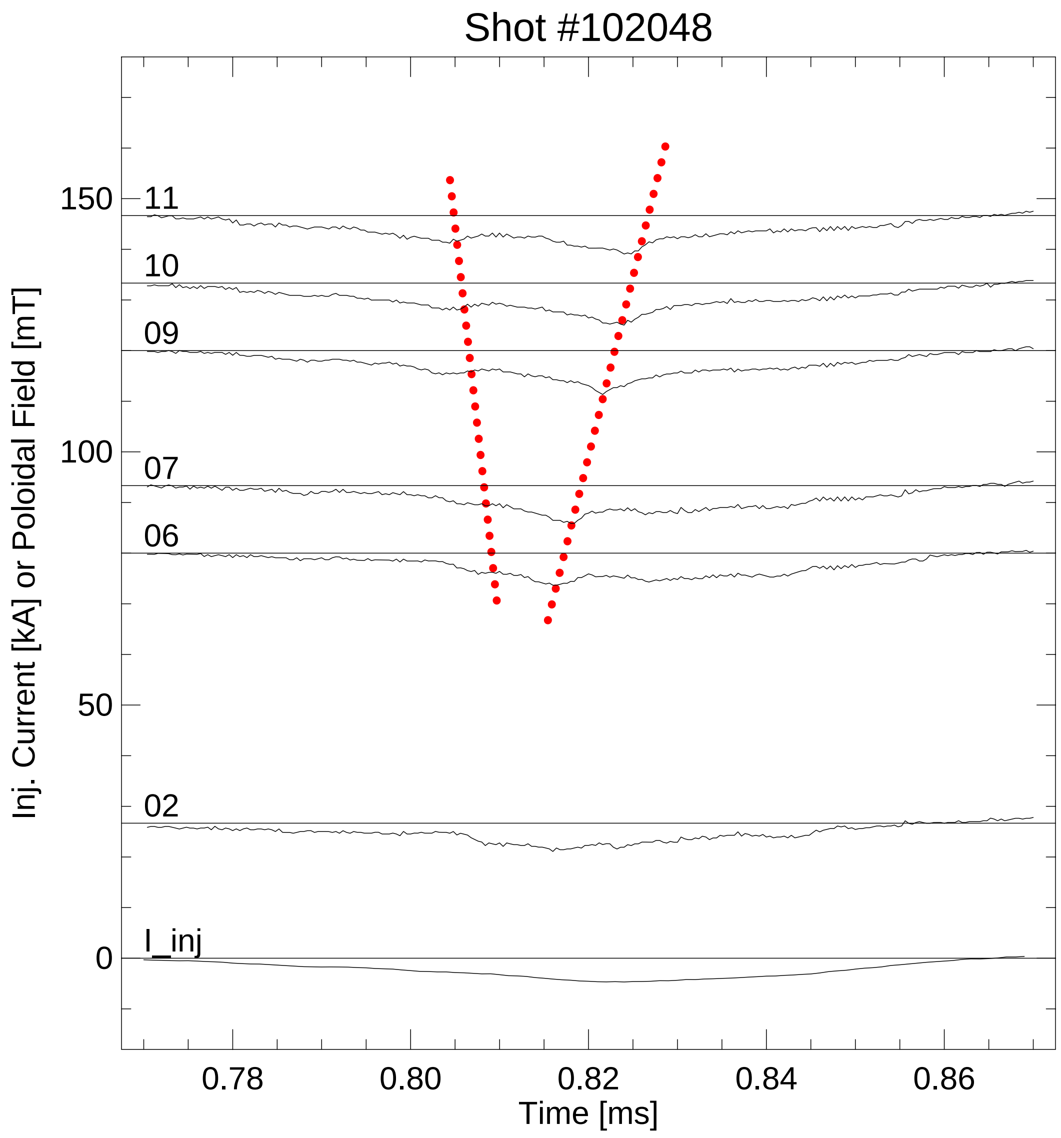
- Preliminary evidence exists for an n=0 (toroidally symmetric) component in the equilibrium region
- Observed on the shell flux loops, but is not strong enough to appear on the surface magnetic field probes.
- The direction of the current suggests the electrons are following the rotating field at the geometric axis.
- Higher input power is required to form a spheromak equilibrium.

The Internal Probe Array Shows the Magnetic Structure of the Injector



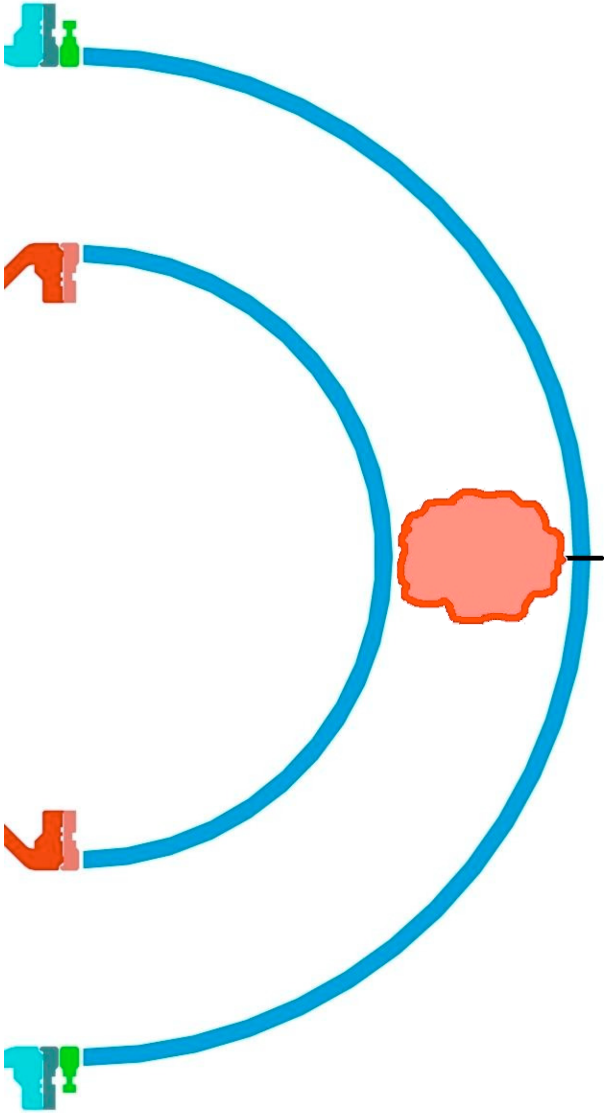
- Injector structure is fairly uniform
- Waveform shape is different from injector Rogowski because probe array breaks symmetry
- Early termination of discharge is probably due to loss of density in injector

Propagating Features are Observed by the Probe Array



- Propagation speed is Alfvénic in magnitude
- Features are observed to travel both directions along the injector
- Speed tends to increase through successive injector cycles

Gas Fuelling Ports Have Been Added To Each Injector



- Ports were added at the outside midpoint of each injector
- A variable fuelling rate can be provided into each injector
- Density is provided where it is needed
- Injector fuelling will reduce the required static fill, allowing higher j/n in the spheromak equilibrium

More Recent Upgrades

- HIT-SI has been moved into the vacuum system from the HIT-II experiment

- Wider diagnostic suite is available, including:
  - » Multi-point Thomson Scattering
  - » Ion Doppler, VUV, SXR Spectroscopy
  - » Dual-beam FIR Interferometry
  - » More data acquisition channels for magnetic diagnostics

- More power supplies are installed

Conclusions

Steady Inductive Helicity Injection (SIHI) has been successfully demonstrated on HIT-SI.

Parameters achieved to date:

- Peak injector currents in excess of 12 kA
- Total power input greater than 2 MW
- Discharge duration over 5 ms

Spheromak formation observations are anticipated for higher power input