Injector Flux and Voltage Control of the Steady Inductive Helicity Injected Torus, HIT–SI


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Abstract

The Steady Inductive Helicity Injected Torus (HIT-SI) is a spheromak with a high-beta ("bow-tie") boundary shape ($R=0.25$ m). The spheromak is produced and sustained by a half-toroid helicity injector at each axial boundary of the flux conserver. Each injector is rotated $90^\circ$ to each other, with respect to the $Z$-axis. External coils on each injector produce sinusoidal flux and loop voltage, such that the total helicity injection rate $dK_{inj}/dt = 2V_{inj}\psi_{inj} \left[ \sin^2(\omega t) + \cos^2(\omega t) \right]$ is constant. This spatial and temporal quadrature of flux and voltage directly produces the rotating non-axisymmetric (predominately $n=1$) toroidal magnetic configuration required for steady-state current drive of the spheromak. Presently, during each half-period the injectors are operated as stabilized pinches transitioning to an RFP, allowing Poynting flow to always be directed inward. The injector coil sets are driven by parallel IGBT switching power amplifiers. The loop voltage coils are driven by a feedback-controlled RLC tank circuit at 5 kHz and the flux coils are directly feedback controlled by pulse-width modulation (using a 50 kHz comparator waveform). Injector currents of up to 11 kA amplitude have been produced for several milliseconds. Fixed phasing of the injector flux and voltage is used to produce the transition between stabilized pinch and RFP injector operation. An improved method has been developed to vary and control phasing of the injector flux during a pulse, with details to be presented.
Overview

- Steady inductive helicity injection (SIHI) drives current in HIT–SI high-$\beta$ spheromak
- HIT–SI helicity injectors transition from stabilized pinches to RFPs each cycle
- Injector flux and loop voltage waveforms are feedback controlled
# HIT Project Personnel

<table>
<thead>
<tr>
<th>Faculty/Staff</th>
<th>Support Staff</th>
<th>Graduate Students</th>
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<tbody>
<tr>
<td>Thomas R. Jarboe</td>
<td>Daniel E. Lotz</td>
<td>William T. Hamp</td>
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<tr>
<td>Brian A. Nelson</td>
<td>Matthew B. Fishburn</td>
<td>Valerie A. Izzo</td>
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<td>Roger Raman</td>
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<td>Paul E. Sieck</td>
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<td>Roger J. Smith</td>
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<td>John A. Rogers</td>
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<td>George R. Andexler</td>
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<th>Undergraduates</th>
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<tr>
<td>Rorm Arestun</td>
<td>Nora Ngyuen</td>
<td>Ling Yu</td>
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<tr>
<td>Ellen Griffin</td>
<td>Chris Pihl</td>
<td>Susan Griffith</td>
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<tr>
<td>Rabih Aboul Hosn</td>
<td>Jonathan Setiawan</td>
<td>Andrew Cassidy</td>
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<td>James Newman</td>
<td>Edwin Penniman</td>
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Introduction

Critical issues for spheromaks include current drive, operation at high $\beta$, and confinement.

The Helicity Injected Torus with Steady Inductive Helicity Injection (SIHI) spheromak, HIT–SI, addresses all of these issues. SIHI features an optimal high-$\beta$ plasma shape and current profile, steady-state operation, minimal plasma-wall interaction, plus injected power and helicity always flow into the plasma.

The prototype HIT–SI experiment “Proto–SI” has commissioned the HIT–SI power supplies.

HIT–SI is replacing the HIT–II spherical torus front end.
Coaxial Helicity Injection (CHI) has Two Relaxation Processes

\[ \dot{K}_{\text{inj}} = 2V_{\text{inj}} \psi_{\text{inj}} \]

\[ \lambda_{\text{inj}} \equiv \frac{\mu_0 I_{\text{inj}}}{\psi_{\text{inj}}} \]

\[ n=0 \Rightarrow n=1 \Rightarrow n=0 \]
$n=1$ Source $\dagger$ Requires only one Relaxation Process

$n=1 \Rightarrow n=0$

$n=1$ source field relaxes to mainly $n=0$ equilibrium in flux conserver

$\dagger$Fernandez et al., Phys. Fluids B, 1(6), 1989
$n=1$ Source Can be Replaced by a Toroidal Pinch

- Source can be an oscillating toroidal pinch
  \[ \dot{K}_{\text{inj}} = 2V_{\text{inj}} \sin(\omega t) \psi_{\text{inj}} \sin(\omega t) \]

- Two toroidal injectors, phased 90°, allow steady inductive helicity injection (SIHI)
  \[ \dot{K}_{\text{inj}} = 2V_{\text{inj}} \psi_{\text{inj}} \left[ \sin^2(\omega t) + \cos^2(\omega t) \right] \]
$n=1$ Source Can be Replaced by a Toroidal Pinch

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- Two toroidal injectors, phased 90°, allow steady inductive helicity injection (SIHI)
  \[ \dot{K}_{\text{inj}} = 2V_{\text{inj}} \psi_{\text{inj}} \left[ \sin^2(\omega t) + \cos^2(\omega t) \right] \]
Stability Calculations: $\beta \sim 10\%$
with “Bow-tie” Flux Conserver
and Hollow $\lambda$ Profile

- All $q_{\text{edge}}$ is on geometric axis
- Bow-tie reduces $q_{\text{edge}} \Rightarrow$ higher $dq/d\psi$
- $\beta \sim 10\%$
HIT–SI Addresses Critical Spheromak Issues

- High-$\beta$ flux conservver shape
- Optimal high-$\beta$ current profile
- Steady-state operation
- Minimal plasma-wall interaction
- Injected power and helicity always flow into the plasma
HIT–SI uses SIHI in a High-$\beta$ “Bow-tie” Flux Conserver

Two (half) toroidal injectors phased 90° in space and time
Details of SIHI: an SIHI Half-Cycle

A) Right injector max flux; left injector zero flux

B) Right injector reducing flux; left injector building up flux

C) Right injector building up flux (reversed from A); left injector reducing flux

D) Right injector full reversal; left injector zero flux
HIT–SI uses Switching Power Amplifiers (SPAs) for $V_{\text{inj}}$ and $\psi_{\text{inj}}$ Control

**Voltage Coil Circuit**
- Mostly resistive
- Driven 5 kHz LC “tank” circuit
- Feedback controlled $V_{\text{inj}}$
- (Eventually $I_{\text{inj}}$ control)

**Flux Coil Circuit**
- Mostly inductive
- Direct pulse width modulation (20 pulses per cycle)
- Feedback controlled $\psi_{\text{inj}}$
HIT SPAs are Modular/Rack-mounted

SPA boxes

IGBTs, driver boards, and caps
## HIT–SI Power Supply Systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Voltage Circuit</th>
<th>Flux Circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(2 ea, 90° phasing)</td>
<td>(2 ea, 90° phasing)</td>
</tr>
<tr>
<td>Waveform Frequency</td>
<td>5 kHz</td>
<td>5 kHz</td>
</tr>
<tr>
<td>Load Type</td>
<td>Plasma Secondary (mostly resistive)</td>
<td>4 × 12-turn Coils (mostly inductive)</td>
</tr>
<tr>
<td>$I_{\text{max}}$</td>
<td>32 kA</td>
<td>96 kA-turns</td>
</tr>
<tr>
<td>Load Impedance</td>
<td>20 mΩ</td>
<td>~ 170 µH</td>
</tr>
<tr>
<td>SPAs in Parallel</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td>Feedback Method</td>
<td>Push-Pull LC tank</td>
<td>Direct PWM(^\ddagger) drive</td>
</tr>
<tr>
<td>Comparator</td>
<td>5 kHz</td>
<td>50 kHz</td>
</tr>
<tr>
<td></td>
<td>(“MW” carrier)</td>
<td>(Triangle carrier)</td>
</tr>
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\(^\ddagger\)Pulse width modulation
SPA: IGBTs in an “H-Bridge”

Each HIT–SI “switching power amplifier” (SPA) uses $2 \times 4$ 1700V/400A IGBTs, and can be pulsed to $\pm 1600$ A at 1 kV.
PWM Determines Flux Circuit Switching Signals

\[
\text{Error} = \text{Demand} - \text{Feedback}
\]

Triangle Comparator Waveform

\[
\text{~Error}
\]
Switching signals S1–S4 are digital fiber optic.
Successive timing of S1–S4 determines V time history.
$V_{inj}$ Driven by Push-Pull LC Tank

- Tank driven with 5 kHz squarewave
- Load current measured against modulated demand envelope
- “MW” comparator waveform invokes push-pull drive of tank
  ⇒ Feedback control of current envelope
Power Flow Always Inward by Controlling Flux and Voltage Phase

Injector plasma inductance causes $V_{\text{inj}}$ to lead $I_{\text{inj}}$.
\[ \Rightarrow \] Constrain $\psi_{\text{inj}}$ to lead $I_{\text{inj}}$ by phase $\delta_0$ to prevent outgoing power during de-fluxing of injector plasma.

- Adjust $\delta_0$ to have $I_{\text{inj}}$ and $V_{\text{inj}}$ cross zero at the same time
- Spheromak and other injector circuit will aid de-fluxing of plasma secondary
- $\lambda_{\text{inj}} = \mu_0 I_{\text{inj}}/\psi_{\text{inj}}$ averages to injector eigenvalue

\[ \Rightarrow \] Power flow into spheromak, not insulator
Injectors: Stabilized Pinch during Flux Buildup, RFP during Flux Reduction

During flux buildup
\[ \lambda_{\text{inj}} < \lambda_0, \text{stabilized pinch} \]

During flux reduction
\[ \lambda_{\text{inj}} > \lambda_0, \text{RFP} \]
Flux Circuit is Fedback to Voltage Tank Circuit

Demand current for one injector phasing:

\[ I_{\text{inj}}^{\text{DEM}} = I_0(t) \sin(\omega_0 t) \]

Ideal injector flux demand (with phase lead \( \delta_0 \)) is:

\[ \psi_{\text{inj}}^{\text{DEM}} = \psi_0(t) \sin(\omega_0 t + \delta_0) \]

Which can be approximated as:

\[ \psi_{\text{inj}}^{\text{DEM}} \approx \frac{\mu_0 \cos \delta_0}{\lambda_0} I_{\text{inj}}^{\text{Actual}} + \psi_0(t) \sin \delta_0 \cos \omega_0 t \]

\( \Rightarrow \) \( \psi_{\text{inj}} \) feedback to \( I_{\text{inj}}^{\text{Actual}} \) corrects voltage circuit phase errors to first order. Flux modifications for startup can also be added.
Flux and Voltage Phase is Controlled by Analog Circuit

On PWMs: 
F = Feedback In
D = Demand In
CWI = Comparator Waveform In
O = Integrated Output (of F)

24—APR—2003
BAN/DEL
HIT–SI Initial Ops: Systems Test

- Non-optimized vacuum chamber and pump
- Limited number of power supplies
  - 8 SPAs each voltage circuit
  - 2 SPAs each flux circuit
- Limited diagnostics
  - Surface probes and flux loops
  - One $H_{\alpha}$ chord
  - CCD image integrated over pulse
  - Limited DAS channels
- Voltage Circuit feedback to coil current
Initial Operation has Inward Only Power Flow and Nearly SIHI
Fixed Phase Control Makes $\psi_{\text{inj}}$ Lead Current and Voltage

$\psi_{\text{inj}}$ phase lead $\Rightarrow V_{\text{inj}}$ and $I_{\text{inj}}$ in phase
X Injector - Shot 102167

- Injector Plasma Current
- Injector Flux
- Injector Flux Circuit Current
- Injector Lambda
- Reversal Parameter
- Pinch Parameter

Time [ms]
HIT–SI Injectors Transition from Stabilized Pinches to RFPs

X Injector: Shot 102167, 1.06-1.95 ms
HIT–SI is Replacing the HIT–II Experimental Front End

- Better vacuum chamber and pumping
- More power supplies
  - $8 \rightarrow 20$ SPAs each voltage circuit
  - $2 \rightarrow 4$ SPAs each flux circuit
- Full HIT–II diagnostic suite
  - Multipoint Thomson Thomson scattering
  - Ion Doppler, VUV, SXR spectroscopy
  - Dual beam FIR interferometry
  - Improved DAS
- Voltage Circuit feedback to $I_{inj}$
Future Work

- Improve HIT–SI operational parameters
- Improve SPA controllers
  - More flexible and programmable
  - FPAAAs and digital circuitry for flexibility
- Add equilibrium coils for long pulses
- Add stability coils for $n=1$ tilt and shift modes (if needed)
  - Rotating $n=1$ drive may mitigate these modes
Summary

- HIT–SI uses SIHI for formation and sustainment of a high-$\beta$ spheromak
- Helicity injectors transition from stabilized pinches to RFPs during a cycle
  - Power flow is always inward
- Improved feedback control will allow flux phasing control during a pulse, leading to time-varying $\lambda_{inj}$ optimization