The Helicity Injected Torus (HIT) Program


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Abstract

• The purpose of the Helicity Injected Torus (HIT) experiment is to develop current drive techniques for low-aspect-ratio toroidal plasmas.

• The present HIT-II spherical tokamak device is capable of driving current using both Coaxial Helicity Injection (CHI) and Ohmic transformer drive.

• The HIT-II device is modestly sized (major radius 0.3 m, minor radius 0.2 m, on-axis toroidal field up to 0.5 Tesla), but has demonstrated toroidal plasma currents of up to 250 kA, using a combination of CHI and Ohmic drive.

• Recent HIT-II experiments have included
  – Current drive mixing scenarios
  – Optimization of CHI-only operations
  – Detailed physics studies of low-aspect-ratio plasmas

These physics studies are enabled by an improved diagnostic set, including
  – Multi-chord FIR interferometry
  – Multi-Point Thomson scattering
  – Triple Langmuir probes

• In the near future, the HIT-II device will be replaced by the Helicity Injected Torus with Steady Inductive helicity injection (HIT-SI), a device capable of generating and sustaining a high-beta low-aspect-ratio toroidal plasma. The final design of the HIT-SI device, and construction milestones, will be presented.
The HIT-II Spherical Torus

TF Coil Frame

Toroidal Insulator (one each end)

Transformer Coils

Absorber Region

Equilibrium Coils

Inner Conductor

Confinement Region

Surface Probes

Tapered Injector Region

Thin Shell

1 meter
The HIT-II Spherical Torus

- HIT-II Engineering Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius $R$</td>
<td>0.3m</td>
</tr>
<tr>
<td>Minor Radius $a$</td>
<td>0.2m</td>
</tr>
<tr>
<td>Aspect Ratio $A$</td>
<td>1.5</td>
</tr>
<tr>
<td>Elongation $\kappa$</td>
<td>1.75</td>
</tr>
<tr>
<td>Ohmic Flux Available</td>
<td>60 mWb</td>
</tr>
</tbody>
</table>

- HIT-II Achieved Plasma Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ohmic</th>
<th>CHI</th>
<th>CHI+OH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Length</td>
<td>60 ms</td>
<td>25 ms</td>
<td>40 ms</td>
</tr>
<tr>
<td>Peak Current</td>
<td>200 kA</td>
<td>240 kA</td>
<td>250 kA</td>
</tr>
<tr>
<td>Density $\bar{n}_e$</td>
<td>$\leq 5 \times 10^{19}$ m$^{-3}$</td>
<td>$1-6 \times 10^{19}$ m$^{-3}$</td>
<td>$\leq 5 \times 10^{19}$ m$^{-3}$</td>
</tr>
</tbody>
</table>

- HIT diagnostics include:
  - Multi-point Thomson Scattering
  - Scannable two-chord FIR interferometer
  - Scannable single-chord 16-channel Ion Doppler Spectrometer
  - Pair of vacuum-UV (VUV) spectrometers (OVI/OV ratio)
  - Single-chord average-$Z_{eff}$ measurement
  - H-\textalpha visible light detectors
  - Surface magnetic triple probes
  - Bolometer (total radiation emission)
  - Internal magnetic and Langmuir probes
  - SPRED
  - Multi-chord soft X-ray (SXR) camera
  - Transient Internal Probe (TIP)
HIT-II Active Flux Control System

- The HIT-II passive flux conserver is:
  - 6mm Stainless-Steel shell ($L/R \approx 1.2\text{ms}$)
  - 3.5mm S-S central column, covered by 12mm of graphite

- For timescales longer than the $L/R$ time, HIT-II boundary fluxes are controlled by an active feedback system:
  - 24 flux loops (14 in the center-column, 10 on the shell)
  - Measured fluxes compared to pre-programmed flux demands
  - Currents in 28 Poloidal Field Coils (PFCs) are adjusted to correct differences between measured fluxes and demands

- The flux demand functions can be used to specify the following throughout a discharge:
  - **Loop voltage**
  - Divertor flux (single- or double-null)
  - Vertical field

- Feedback system can respond to any axisymmetric displacement, and controls the plasma position and shape in real time
HIT–II Ohmic Plasmas

• Peak currents of 200 kA (limited or diverted)

• Reconnection events observed during discharges, usually during current decay phase.

  These helicity-conserving events are characterized by:
  – Growing low-$n$ precursor modes
  – Degradation of plasma confinement
  – Rapid change in equilibrium ($< 100 \, \mu\text{sec}$)
    ⇒ Current profile relaxes to more uniform $J/B$

• Preliminary Thomson scattering shows $T_e > 100\text{eV}$

• Average $n_e$ is significant fraction of Greenwald

• IDS shows $T_i \approx 50–100 \text{eV}$
HIT-II Ohmic Shot 19347 (HIT-like divertor)

**Plasma Current**

**Loop Voltage**

**Electron Density**

**Toroidal Field Fluctuations**

0 10 20 30 40

-0.6 -0.3 0.0 0.3 0.6

Time (ms)

0 10 20 30 40

-0.6 -0.3 0.0 0.3 0.6
EFIT Reconstruction of HIT-II Discharges

- EFIT reconstructions of HIT-II discharges are undergoing continual improvement. Presently, HIT-II EFITs utilize:
  - Toroidal plasma current, diamagnetic flux and current on the driven flux ($I_{\text{inj}}$)
  - 24 poloidal flux loops
  - 18 Rogowski segments measuring poloidal field
  - 19 poloidal magnetic surface probes
  - Realistic estimates for measurement errors

- The fit functions are of the following form:

\[
FF_1'(y) = \gamma_{10} \quad \text{(below the X-point)}
\]
\[
FF_2'(y) = \gamma_{20} + \gamma_{21}y \quad \text{(above the X-point)}
\]
\[
p(y) = \alpha_0(1 - y)
\]

where 
\[
y \equiv \frac{\psi - \psi_{\text{axis}}}{\psi_{\text{abs}} - \psi_{\text{axis}}}
\]

and $\psi_{\text{abs}}$ is the poloidal flux in the absorber region

- Qualitatively, reconstructions fit measurements acceptably. Quantitatively, overall error $\leq 10^{-4}$, but $\chi^2 \ll 64$.

- In the near future, HIT-II EFITs will also utilize:
  - 24 F-coil currents (code is being verified)
  - 12 surface $I_{\text{inj}}(\psi)$-probes
  - Multi-point Thomson scattering data
  - Internal magnetic probing data
CHI Tokamaks

• Define the current drive efficiency $\epsilon$ as

$$\frac{1}{\epsilon} \equiv \frac{\lambda_{\text{INJ}}}{\lambda_{\text{TOK}}}$$

where

$$\lambda_{\text{TOK}} \equiv \frac{\mu_0 I_p}{\psi_{\text{TF}}} \quad \text{and} \quad \lambda_{\text{INJ}} \equiv \frac{\mu_0 I_{\text{INJ}}}{\psi_{\text{INJ}}}$$

• The injector current $I_{\text{INJ}}$ is

$$I_{\text{INJ}} = \frac{8\psi_{\text{INJ}}^2 \mu_0^2}{\mu_0 d^2 I_{\text{TF}}}$$

where $d$ is the inter-electrode distance, $\psi_{\text{INJ}}$ is the injector flux and $I_{\text{TF}}$ is the current generating the TF. (see Nelson, et al., Nuclear Fusion 34, 1111 (1994) and Jarboe, Fusion Technology 15, 7 (1989))

• This implies a CHI-driven plasma current of

$$I_p = \left( \frac{8S_{\text{TF}}}{\mu_0 \pi} \right) \left( \frac{\epsilon \psi_{\text{INJ}}}{d^2} \right)$$

where $S_{\text{TF}}$ is a parameter with units of length, determined by the geometry of the device:

$$S_{\text{TF}} \equiv \frac{\pi \psi_{\text{TF}}}{\mu_0 I_{\text{TF}}}$$
Difficult to “Prove” Closed Flux in CHI Plasmas

• Ohmic plasmas have a $B_p$ structure that “obviously” indicates closed flux:
  – Up-down symmetric
  – Hoop force pushes the magnetic axis outward
High-performance CHI plasmas (in HIT and HIT-II) have $B_p$ structure consistent with closed flux.

• When a continuous $n=1$ mode is present:
  – Absorber shorting current drops to nearly zero (HIT and HIT–II)
  – Spectroscopy shows increasing temperature (HIT, HIT–II, NSTX)
  – $T_e \sim 100$ eV (HIT single-point Thomson)
  – EFIT converges (HIT and HIT–II)

• Need additional evidence:
  – Internal measurements (e.g., MPTS)
  – Toroidal plasma current significantly greater than the open-flux prediction:

$$I_p > I_{p-\text{OPEN}} = \left( \frac{8S_{\text{TF}}}{\mu_0 \pi} \right) \left( \frac{\epsilon \psi_{\text{INJ}}}{d^2} \right)$$
These low-current CHI plasmas are not expected to have significant amounts of closed poloidal flux.
HIT-II CHI $I_{TF}$ Scan - Staggered SB rows, both guns, both puffs

Injector Current

Plasma Current

TF Current

$V_{TF} = 8\text{ kV}$
$V_{TF} = 7\text{ kV}$
$V_{TF} = 6\text{ kV}$
$V_{TF} = 5\text{ kV}$
$V_{TF} = 4\text{ kV}$
These low-current CHI plasmas are not expected to have significant amounts of closed poloidal flux.
HIT–II CHI Plasmas

- Peak currents of up to 240 kA
- Continuous high-frequency $n=1$ mode observed in all high-performance discharges
- Measured ion flows consistent with dynamo model for helicity injection current drive
- Plasmas can be generated at a relatively low density ($n_e \leq 2 \times 10^{19} \text{ m}^{-3}$)
- Unbalanced double-null divertor boundary improves the plasma performance, compared to single-null:
  - Less shorting current across absorber gap
  - Better shot-to-shot reproducibility
  - Relatively low impurity radiation
HIT-II #23225 - Double-Null CHI, 10 mWb Inj

Plasma Current

Injector Voltage

Injector Current

Poloidal Field Fluctuations

\( \frac{\delta B_{p-S7}}{B_{p-S7}} \) (%)

Time (ms)
CHI Startup of Ohmic HIT-II Plasmas

- Recent HIT-II experiments have used a CHI pulse to ionize and form a seed ST for Ohmic current drive.

- CHI startup has significant advantages over Ohmic-only operation:
  - Substantial Volt-second savings (or, higher peak plasma current)
  - Better shot-to-shot reproducibility
  - Less sensitivity to wall conditions

- CHI startup plasmas have demonstrated 250 kA of toroidal plasma current in HIT-II, far higher than any Ohmic-only plasma.
CHI Startup Technique

Sequence:

1. Discharge begins as typical CHI plasma
   (using high voltage, low capacitance Formation Bank)

2. Injector flux rapidly brought to zero
   (8 mWb of flux, ramped down in a few milliseconds)

3. As injector flux vanishes, apply Ohmic current drive

Discharge features:

- Interferometry scans reveal that CHI-phase plasma is a thin current sheet near the wall, but that the Ohmic-phase plasma fills the confinement region and has a peaked density profile

- Higher-current, longer-duration CHI pulses generally lead to more captured plasma current, and a higher eventual peak current

- However, in some cases, excessive Formation-Bank voltage can lead to high impurity content, degrading the plasma performance
HIT-II #23927 - CHI-Only Discharge

Plasma Current

$I_p$ (kA)

0
50
100
150

CHI Injector Current

$I_{inj}$ (kA)

0.0 0.5 1.0 1.5 2.0 2.5

Time (ms)

0
2
4
6
8
10

Measured Injector Flux

$\psi_{inj}$ (mWb)

0
50
100
150

$0.0$ $0.5$ $1.0$ $1.5$ $2.0$ $2.5$ Time (ms)

$HIT-II \ #23927 - CHI-Only \ Discharge$

$Plasma \ Current$

$I_p$ (kA)

0
50
100
150

CHI Injector Current

$I_{inj}$ (kA)

0.0 0.5 1.0 1.5 2.0 2.5

Time (ms)

0
2
4
6
8
10

Measured Injector Flux

$\psi_{inj}$ (mWb)

0
50
100
150
Poloidal Flux Contours for HIT-II #23927 (CHI-Only) at $t=1.5$ ms from EFIT reconstruction
CHI+Ohmic Plasmas
Results from EFIT

• Comparing #23917 (CHI startup + Ohmic) and #23918 (Ohmic-only):
  – Both shots used 30 mWb Ohmic flux swings
  – CHI+OH shot reaches peak current of 140 kA, but Ohmic-only discharge reaches only 85 kA
  – Alternatively, CHI startup “saved” 11 mWb of Ohmic flux reaching 85 kA

• #24553 has best HIT-II plasma performance:
  – Peak toroidal plasma current of 250 kA
  – Current decay time of up to 20 ms
  – Peak closed poloidal flux of 40 mWb, using 52 mWb Ohmic flux swing
  – $q_0 < 1$ period correlates with observed sawteeth
  – $\beta_p \approx 1.5$ and on-axis $\beta_T \approx 18\%$
HIT-II #23917 - CHI+Ohmic Discharge

Plasma Current

CHI Injector Current

Measured Loop Voltage

Measured Injector Flux

Poloidal Field Fluctuations

Time (ms)
HIT-II #24553 - CHI+Ohmic Discharge

Plasma Current

CHI Injector Current

Measured Loop Voltage

52 mWb Ohmic Flux Swing

Measured Injector Flux

TF Current

Poloidal Field Fluctuations

δBp-S7/Bp-S7 (%)
Poloidal Flux Contours for
HIT-II #24553 (CHI+OH) at $t=17.5$ ms
from EFIT reconstruction
HIT-II CHI+OH #23925 - Data vs EFIT (tavg=50us)

Measured Loop Voltage

Plasma Current

Paramagnetic Flux

Closed Poloidal Flux

Helicity

K (10^3 Wb^2 Ψ_p^2)

On-axis q

On-axis pressure

On-Axis β_T

EFIT Chi-Squared

Time (ms)
Poloidal Flux Contours for
HIT-II #23925 (CHI+OH) at $t=10.0$ ms
from EFIT reconstruction
HIT-II CHI+OH #23917 - Data vs EFIT Results

Measured Loop Voltage

Plasma Current

Paramagnetic Flux

Closed Poloidal Flux

Helicity

On-axis q

On-axis pressure

On-axis $\beta_T$

EFIT Chi-Squared

Time (ms)
Poloidal Flux Contours for
HIT-II #23917 (CHI+OH) at $t=10.0$ ms
from EFIT reconstruction
HIT-II OH-only #23918 - Data vs EFIT (tavg=0.1ms)

<table>
<thead>
<tr>
<th>Time (ms)</th>
<th>V_{loop} (V)</th>
<th>I_p (kA)</th>
<th>ΔΦ_T (mWb)</th>
<th>Ψ_p (mWb)</th>
<th>K (10^{-3} Wb^2 T^2)</th>
<th>q_0</th>
<th>p_0 (kPa)</th>
<th>\beta_T (%)</th>
<th>\chi^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
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<tr>
<td>60</td>
<td>60</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
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<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Diagram showing measured loop voltage, plasma current, paramagnetic flux, closed poloidal flux, helicity, on-axis q, on-axis pressure, on-axis \beta_T, and EFIT chi-squared over time.
Poloidal Flux Contours for
HIT-II #23918 (Ohmic-only) at $t=10.0$ ms
from EFIT reconstruction
Future Work

• Expand HIT-II physics and current drive studies:
  – Explore other CHI+OH scenarios
  – CHI enhancement of Ohmic plasmas
  – Fluctuation studies
  – Probing studies
  – Confinement and Transport

• Finish construction and begin plasma operations with the Prototype HIT device with Steady Inductive helicity injection (Proto-SI)
The Proto-SI Device:
Design Cross-section
The Proto-SI Device: Under Construction
Summary

• The purpose of the HIT experiment is to develop current drive techniques for low-aspect-ratio toroidal plasmas.

• The present HIT-II spherical tokamak device can drive current using both Coaxial Helicity Injection (CHI) and Ohmic transformer drive.

• Recent HIT-II experiments have included
  – CHI startup with Ohmic operation, producing peak toroidal currents of 250 kA
  – Optimization of CHI plasmas, producing peak toroidal currents of 240 kA

• Improved HIT diagnostic and analysis set has enabled more comprehensive plasma studies than ever before:
  – Multi-chord FIR interferometry
  – Multi-Point Thomson scattering
  – Triple Langmuir probes
  – Routine use of EFIT reconstructions
Reprints of
“The Helicity Injected Torus (HIT) Program”
Magnetic Helicity

Magnetic helicity is a measure of flux linkage. The helicity $K$ is defined by:

$$K \equiv \int (\mathbf{A} \cdot \mathbf{B}) \, dV = \int \int \oint (\mathbf{A} \cdot d\ell) (\mathbf{B} \cdot dS)$$

For two flux tubes, $\phi_1$ and $\phi_2$:

$$K = \int \int \oint_1 (\mathbf{A}_1 \cdot d\ell_1) (\mathbf{B}_1 \cdot dS_1) + \int \int \oint_2 (\mathbf{A}_2 \cdot d\ell_2) (\mathbf{B}_2 \cdot dS_2)$$

That is,

$$K = \phi_2 \phi_1 + \phi_1 \phi_2 = 2\phi_1 \phi_2$$

In a tokamak,

$$K \propto I_p I_{TF}$$
Helicity and Ohmic Current Drive

Ohmic current drive “injects” helicity by adding poloidal flux which links toroidal flux

\[ V_{\text{LOOP}} \text{ “injects” } \dot{\psi}_{\text{POL}} \text{ which completely links } \phi_{\text{TOR}} \]

The helicity injection rate, \( \dot{K} \), is:

\[ \dot{K} = 2V_{\text{LOOP}}\phi_{\text{TOR}} \]
Helicity and CHI Current Drive

Coaxial Helicity Injection (CHI) injects toroidal flux $\dot{\phi}_{\text{TOR}}$ which links the poloidal flux $\psi_{\text{inj}}$

$V_{\text{inj}}$ injects $\dot{\phi}_{\text{TOR}}$ which links $\psi_{\text{inj}}$

$\dot{K} = 2V_{\text{inj}}\psi_{\text{inj}}$
A Helicity Injection
Current Drive Mechanism

• A tokamak with sufficiently hollow current profile and edge vacuum region containing a rational-\(q\) surface is unstable to an \(n=1\) external kink mode (PEST and PEST-3 result; for details, see D. Orvis, PhD Dissertation, Univ. of Washington (1997))

• “Dynamo action”: This \(n=1\) mode dissipates the free energy of the hollow current profile by driving toroidal current in the plasma core, flattening \(J/B\)

• Empirically, the presence of a continuous \(n=1\) mode is required for high-performance CHI plasmas

• Current-profile relaxation and core current drive may not require either magnetic reconnection or multiple modes

• Differential rotation of the electron fluid causes the asymmetry of the \(n=1\) mode structure necessary for dynamo action (K. McCollam, PhD Diss., Univ. of Wash. (2000))
CHI Tokamak Observations
Consistent with Dynamo Model

Experimental results are obtained by reversing the electrode polarity from cathode central-column (CC) to anode central-column, and producing comparable CHI plasmas.

- $n=1$ mode propagates in the $\mathbf{E} \times \mathbf{B}$ direction

- Edge plasma rotates in $\mathbf{E} \times \mathbf{B}$ direction, but plasma core rotates opposite to toroidal current $I_p$

- Cathode CC has larger $n=1$ amplitude than anode CC

- Cathode CC has lower $n=1$ frequency than anode CC

- Cathode CC plasmas exhibit more relaxed current density profiles than anode CC plasmas

- Cathode CC has more ion heating than anode CC
Edge Ion Spin-Up Follows $E \times B$

Cathode CC Opposite to Anode CC

- Line-averaged toroidal velocities from IDS
- Edge chord: impact parameter = 41.4 cm
- CIII emission line: $\lambda = 229.68$ nm
- Cathode CC shot was #16693, Anode CC was #17036
HIT-II CHI Shot 16872 (Cathode CC)

Plasma Current

Injector Voltage

Injector Current

Toroidal Field Fluctuations

Time (ms)