Evidence for Magnetic Relaxation in Coaxial Helicity Injection Discharges in the HIT–II Spherical Torus

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Summary

• New Coaxial Helicity Injection (CHI) regime on HIT–II
  – Toroidal plasma current $I_p$ up to 350 kA
  – $I_p$ greater than $I_{TF}$ in some discharges ($\leq 120\%$)

• Global magnetic measurements indicate that measured $I_p$ can be up to 6 times the wrap-up current $q_aI_{INJ}$

• Internal magnetic measurements show:
  – Buildup of poloidal flux and formation of closed-flux core
  – Relaxation of the current density profile
  – High paramagnetism (up to 40% of vacuum field)

• Current ramp-up rate correlates with the pitch in the magnetic field across the injector
The HIT–II Spherical Torus

HIT–II Engineering Parameters:

- Major Radius \( R = 0.3 \) m
- Minor Radius \( a = 0.2 \) m
- Aspect Ratio \( A = 1.5 \)
- Elongation \( \kappa = 1.75 \)
- 60 mWb Ohmic Flux Available

Active poloidal-flux boundary feedback control system
(response time < 1 ms)

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The HIT–II Spherical Torus

HIT–II plasma parameters achieved:

<table>
<thead>
<tr>
<th></th>
<th>Ohmic</th>
<th>CHI</th>
<th>CHI Startup</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>300 kA</td>
<td>350 kA</td>
<td>300 kA</td>
</tr>
<tr>
<td>Density $\bar{n}_e$</td>
<td>$\leq 5 \times 10^{19}$ m$^{-3}$</td>
<td>$1-10 \times 10^{19}$ m$^{-3}$</td>
<td>$\leq 5 \times 10^{19}$ m$^{-3}$</td>
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HIT diagnostic systems include:

- Internal magnetic and Langmuir probes
- Scannable two-chord FIR interferometer
- 16-channel Ion Doppler Spectrometer, scannable single-chord
- Multi-point Thomson Scattering
- Pair of VUV spectrometers (OVI/OV ratio)
- H-α visible light detectors
- Surface magnetic triple probes
- Bolometer (total radiated power)
- SPRED
- Single-chord $\bar{Z}_{\text{eff}}$ measurement

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CHI-driven $I_p$ up to 353 kA

$I_p$ is total (open- and closed-flux) toroidal plasma current.

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CHI-driven $I_p$ Above 300 kA

$I_p$ is total (open- and closed-flux) toroidal plasma current.

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CHI-driven $I_p$ up to 120% of $I_{TF}$

$I_p$ is total (open- and closed-flux) toroidal plasma current.

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Optimum $I_{TF}$ for CHI-Driven $I_p$ on HIT–II

- Peak plasma current $I_p$ in 307 shots, versus corresponding $I_{TF}$
- $I_p$ can be maximized for $I_{TF} \approx 500$ kA
- Wall conditions can produce significant shot-to-shot variations, and can limit plasma performance early in a run campaign

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**CHI-Driven $I_p$ Consistent With Taylor Relaxation**

- Peak $\lambda_{TOK}$ in 307 shots, versus post-formation $\lambda_{INJ}$

  \[ \lambda_{INJ} = \frac{\mu_0 I_{INJ}}{\psi_{INJ}} \quad \text{and} \quad \lambda_{TOK} = \frac{\mu_0 I_p}{\phi_{TF}} \]

- Solid line is $\lambda_{TOK} = \lambda_{INJ}$, dashed line is $\lambda_{TOK} = (1.1)\lambda_{INJ}$

- Generally, $\lambda_{TOK} \leq \lambda_{INJ}$, which agrees with Taylor relaxation

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Discharge #29133: peak $I_p$ was 290 kA, while $I_{TF} \approx 470$ kA, for peak $I_p/I_{TF}$ of 62%.
Peak $I_p/qI_{INJ} \approx 6$, while peak $I_p/qI_{BANK}$ is nearly 2.
Discharge #29988: peak $I_p$ was 210 kA, while $I_{TF} \approx 175$ kA, for peak $I_p/I_{TF}$ of 120%.

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IDS-Measured $T_i$ up to 300 eV

$T_i$ and $\bar{v}_{TOR}$ measured by single-chord Ion Doppler Spectroscopy, tuned to OV emission (278 nm) on edge chord (impact parameter of 0.44 m). Negative $\bar{v}_{TOR}$ is counter to $I_p$.

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Internal Magnetic Probe Array

- Each probe “stem” contains 5 or 8 magnetic triple probes, with Boron-Nitride sheaths, stem axes spaced 35 mm apart
- Three probe stems are spaced poloidally and toroidally to enable calculations of the current density $J$
- Shallow probing (90 mm insertion) was found to be only slightly perturbing for these discharges
- Deeper probing (150 mm insertion) significantly degraded plasma performance, generally reducing peak $I_p$ by 20%

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Probes Show Poloidal Flux Generation

- Rapid rise in $I_p$ corresponds to the “bubble-burst”, and probe-measured flux is simply the injector flux $\psi_{INJ}$ (6.0 mWb, lower dashed line).
- Slow post-formation rise in $I_p$ corresponds to increasing probe-measured flux.
- Peak measured flux is larger than the total vacuum flux that could be in the confinement region ($\sim11$ mWb, upper dashed line).

Vacuum Fluxes for HIT–II CHI Shot #29388

Discharge #29388 flux boundaries are Unbalanced Double-Null Divertor, with:
- Injector flux $\psi_{INJ} = 6.0 \text{ mWb}$
- “Absorber null flux” $\psi_{INJ} = 2.5 \text{ mWb}$
- Vertical flux up to 4.0 mWb at midplane

Internal magnetic probes can have up to 2 mWb of vertical flux behind the tips for 150mm insertion (as shown)

Open flux in confinement region may be up to 11 mWb for 90 mm insertion, assuming $\psi_{INJ}$ is completely drawn out.

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$J(R)$ is initially hollow. During slow $I_p$ rise, current density migrates inward.

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Low-TF Plasmas Can Be Strongly Paramagnetic

Paramagnetic toroidal fields reach 40% of the vacuum toroidal fields.

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Note the Slow $I_p$ Rise After Formation

- Initial fast rise in $I_p$ is related to bubble-burst, and probing indicates that the current is flowing on open field lines
- Slower post-formation rise in $I_p$ is related to relaxation and the formation of a closed-flux core
- This current rise $dI_p/dt$ correlates with high injector flux, relative to the toroidal field

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Even for High $B_T$, Increasing $\psi_{INJ}$ Allows Relaxation and Current Build-Up

Shot series with relatively high toroidal field ($I_{TF} \approx 800$ kA)

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Current Ramp-up Rate Correlates with Injector Field-Line Pitch

\[
\text{pitch} \approx \tan^{-1}\left( \frac{2|B_{p-\text{INJ}}|}{|B_T|} \right)
\]

where \(B_{p-\text{INJ}}\) is the poloidal field due to the injector flux and \(B_T\) is the vacuum toroidal field in the injector. Data plotted for 307 discharges.

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A Minimum Field Pitch May Be Needed for Relaxation to Overcome Resistive Decay

- Relaxation rates vary with field-line geometry:
  Antiparallel field lines reconnect faster than parallel field lines.
  [Y. Ono et al, Phys. Fluids B 5, 3691 (1993)]

- Strong toroidal fields in a Spherical Tokamak
  ⇒ Fields are nearly parallel in the HIT–II injector
  ⇒ Slow magnetic relaxation rate

- Decreasing $I_{TF}$ and/or increasing $\psi_{INJ}$ will increase
  the magnetic field pitch in the injector region

- Experimentally, there is a minimum field pitch needed for
  significant buildup of the toroidal plasma current
  ⇒ Minimum relaxation rate needed to overcome resistive decay

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Summary

- New HIT–II CHI operating regime has been explored:
  - Toroidal plasma current $I_p$ up to 350 kA
  - $I_p$ greater than $I_{TF}$ in some discharges ($\leq 120\%$)
  - Consistent with Taylor relaxation ($\lambda_{TOK} \leq \lambda_{INJ}$)
  - $I_p$ can be up to 6 times the wrap-up current $q_a I_{INJ}$

- Relatively high temperatures:
  - IDS $T_i$ typically 100-300 eV and MPTS $T_e$ up to 100 eV

- Internal magnetic measurements show:
  - Buildup of poloidal flux and formation of closed-flux core
  - Relaxation of the current density profile
  - Strongly paramagnetic at low TF (up to 40% of vacuum)

- Current ramp-up rate correlates with injector field-line pitch
  - Excess TF inhibits relaxation and current drive

Future Work

• Continue analysis:
  – Discharges with NSTX-like injector geometry
    ★ Do these discharges follow the field-pitch scalings?
  – More detailed probing results:
    ★ Overall scalings?
    ★ $n=1$ mode structure?
    ★ Formation dynamics?
  – Correlate (if possible) other discharge features:
    HXR pulses, slow $P_{\text{RAD}}$ oscillations

• EFIT equilibrium reconstructions, with and without fitting to internal probe measurements

• Do corresponding CHI studies on NSTX

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Magnetic Helicity

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

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

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

$$K = \int \int \oint_1 (A_1 \cdot d\ell_1) \, (B_1 \cdot dS_1) + \int \int \oint_2 (A_2 \cdot d\ell_2) \, (B_2 \cdot dS_2)$$

That is,

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

In a tokamak,

$$K \propto I_p I_{TF}$$

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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 $\psi_{\text{inj}}$

$\dot{K} = 2V_{\text{inj}}\psi_{\text{inj}}$

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Model for ST CHI Injector

• As described in:
  Jarboe, *Fusion Technology* 15, 7 (1989), and Nelson *et al.*, *Nuclear Fusion* 34, 1111 (1994)

• Describes a CHI discharge in terms of current flowing on open flux connecting the injector electrodes.

• Injector flux remains in the injector unless the injected current passes a threshold: the bubble-burst current.

• Above this threshold, the injector flux is drawn into the confinement region, and the steady-state injector current will be clamped to the bubble-burst value.

• For large $A$, the bubble-burst $I_{\text{inj}}$ is

\[
I_{\text{inj}} = \frac{\chi^2 \psi_{\text{inj}}^2}{\mu_0^2 d^2 I_{\text{TF}}}
\]

where $\chi$ is a dimensionless number, $\psi_{\text{inj}}$ is the injector flux, $d$ is the inter-electrode distance, and $I_{\text{TF}}$ is the current generating the TF.

• The measured electrode voltage can be affected by rapid changes in the field-line lengths.
Empirical CHI Scaling Studies

- Utilized sets of single-null CHI discharges with variations in injector flux magnitude $\psi_{INJ}$, toroidal field current $I_{TF}$ and injector geometry (effectively, $d$).

- Found that, as expected, the injector current scales as
  \[ I_{INJ} \propto \psi_{INJ}^2 / I_{TF} \]
  and that open-flux toroidal plasma current scales as
  \[ I_p \propto \psi_{INJ} \]
  That is, the open-flux toroidal plasma current has no dependence on $I_{TF}$

- The injector current did not scale as $1/d^2$.
  Instead, given $\psi_{INJ}$ and $I_{TF}$, the injector current was minimized for an “NSTX-like” injector flux geometry.
$I_{INJ}$ Scales as $\psi_{INJ}^2 / I_{TF}$

HIT-like 6.5 mWb, Both guns, Inner puff, $V_{SB} = 94\%$

Injector Current vs TF

Each point is a 1ms interval in a single discharge

$I_{inj} = C / I_{TF}$

Injector Current vs $\Psi_{inj}$

t = 2.00 ms in all shots, avgd over 1.00 ms

$I_{inj} = C^* \Psi_{inj}^2$

Bottom gun, Inner and Top gun puff

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$I_{\text{INJ}}$ Minimized for NSTX-like Injector

Each point represents 1 ms interval in one discharge
10 Rows at 90%, Both Guns, Both Puffs

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