Internal Magnetic Probing of HIT-II CHI Plasmas

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Abstract

The HIT-II device, a low aspect ratio (R_o=0.3m, a=0.2m) torus with B_t = 0.5T on axis, operates with both inductive drive and Coaxial Helicity Injection (CHI) to initiate and sustain the plasma equilibrium. Recently, a CHI operational regime has been found that shows a significant departure from previous plasma behaviour and may be attributed to Taylor relaxation to a more Spheromak-like equilibrium. These plasmas have produced record plasma currents of 350kA. An internal magnetic probe consisting of an array of eight 3d coils spanning 8.8cm has successfully probed these plasmas to a depth of 15cm. Internal field measurements have shown the relaxed plasmas have significantly higher poloidal flux than the bias injector flux and that the plasmas are highly paramagnetic. Only the highest current discharges and 15cm probing depths have shown significant probe perturbations (20% degradation in Ip) and even these shots demonstrate the typical dynamics of the relaxed plasmas. The internal field structure and dynamics of the two CHI operational modes are described and compared. Also, the transient bubble burst initiation of the CHI plasmas and the ubiquitous n=1 rotating mode is well characterized by the probe and will be described.
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*46th APS-DPP meeting, Savannah, Ga, Nov 15-19, 2004*
Overview of Coaxial Helicity Injection

<table>
<thead>
<tr>
<th>Dynamic Formation</th>
<th>Steady State Injection</th>
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<tr>
<td>JxB Force Produces Bubble Burst</td>
<td>Edge Current Relaxes Toward Magnetic Axis</td>
</tr>
</tbody>
</table>

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\[ \frac{dK}{dt} = 2 \cdot \Psi_{inj} \cdot V_{inj} \]

\[ \lambda_{inj} = \frac{\mu_0 \cdot I_{inj}}{\psi_{inj}} \]

\[ I_{inj} \propto \frac{\psi_{inj}^2}{\mu_0^2 \cdot d^2 \cdot I_{tor}} \]

\[ I_{toroidal} \approx I_{inj} \cdot \left( \frac{\psi_{tor}}{\psi_{inj}} \right) \]

**HeliCITY INJECTION RATE**

\( (J/B) \), ‘\text{LAMBDA}’ OF THE \text{INJECTOR}

\( \psi_{inj} \) AND THE INTER-ELECTRODE DISTANCE \( (d) \) DETERMINE \( I_{inj} \)

**WIND-UP FACTOR**
Evidence for Taylor relaxation and poloidal flux generation in HIT-II CHI discharges

- A new operating regime has been developed for CHI discharges using an asymmetric double null magnetic topology and demonstrating peak plasma currents, $I_p$, over 350kA and a peak $I_p/I_{rf}$ ratio of 1.2.

- The $I_p$ current rise after ‘bubble burst’ produces currents greater than twice the $2q_aI_{inj}$ wrap-up current expected from edge current on open flux strongly suggesting a closed flux plasma core.

- The mid-plane poloidal flux as measured by the internal magnetic probe greatly exceeds the injector flux (the maximum).

- $I_p$ seems to saturate at a level suggesting that the $j/B$ of the main chamber, $\lambda_{tok}$, has risen to the injector $j/B$, $\lambda_{inj}$.

‘The HIT-II Spherical Torus: Physics and Key Experimental Results’, A.J. Redd, [PP1.022], Thursday afternoon
**CHI Relaxation Phenomena**

- an asymmetric mode is required to drive toroidal currents on closed field lines in steady state (no inductive loop voltage). An asymmetric ‘dynamo’ mode. [Cowling’s theorem]

- The ubiquitous rotating N=1 mode is suspected to be the mode necessary for driving edge current relaxation across the core plasmas separatrix.

- The HIT-II device has been probed using an internal probe to characterize the poloidal flux distribution of the N=1 rotating mode for CHI discharges showing no-relaxation is taking place and CHI discharges showing relaxation with the mode present
Internal Magnetic Probe

Measures radial profiles of all three field components: poloidal, toroidal and radial magnetic fields. Also has the capability of measuring local plasma current, \( j_e \), with off axis stems.

- Stainless steel vacuum system using 5.33mm dia., 0.13mm wall thickness tubing and mini-conflat vacuum flange. A 25.4cm linear actuator is used.
- Three stems for measuring fields with a toroidal/poloidal displacement
- Boron nitride shield, 0.1cm thick.
- Central radial array of 8, 3-d pickup coils, \( \sim 300\text{mm}^2 \) area, spaced 1.25cm apart
- Off axis radial arrays of 5, 3-d pickup coils with poloidal and toroidal offsets to measure local current
- Bandwidth in excess of 150kHz.
2.5kV TF, Relaxation CHI Discharges
Combined Shots: 30051/30055 LP filtered Pol(r) and Tor(b) Fields Vs R and t

Field Strength [T]

Time [ms]

2.5kV TF field (vacuum)
3.0kV TF, Relaxation CHI Discharges

Plasma Current and Outer Pol. probe, 3.0kV TF Discharges, Psi-Inj=7.7mWb

<table>
<thead>
<tr>
<th>SHOTS</th>
<th>Probe Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>30044</td>
<td>52cm</td>
</tr>
<tr>
<td>30045</td>
<td>52cm</td>
</tr>
<tr>
<td>30047</td>
<td>52cm</td>
</tr>
<tr>
<td>30049</td>
<td>52cm</td>
</tr>
</tbody>
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3.5kV, TF Relaxation CHI Discharges
Combined Shots: 30030/30034 LP filtered Pol(r) and Tor(b) Fields Vs R and t

3.5kV TF field (vacuum)

Field Strength [T]

Time [ms]

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5kV, TF Relaxation CHI Discharges

Plasma Current and Outer Pol. probe, 5kV TF Discharges, Psi-Inj=10.1mWb

Current [kA]

Voltage/20 and $I_{SB}$

Radiated Power

Toroidal Flux Loop

Rad. Power [MW]

SHOTS  Probe Position:
29890  52cm
29891  52cm
29892  44.5cm
29893  44.5cm
29894  52cm
29895  52cm
29896  52cm

Time [ms]
Combined Shots: 30030/30034 LP filtered Pol(r) and Tor(b) Fields Vs R and t

Field Strength [T]

Time [ms]

3.5kV TF field (vacuum)
Combined Shots: 29891/29893 Pol(r) and Tor(b) Flux Vs R and t

Pol. Flux [mWb/M] & Tor. Flux [mWb/M]

Psi-inj flux

5kV TF Vac. Tor. Flux [mWb/M] from shell

Time [ms]

0 1 2 3 4 5 6 7

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7kV TF Relaxation CHI Discharges
Combined Shots: 29897/29900 LP filtered Pol(r) and Tor(b) Fields Vs R and t

Field Strength [T]

Time [ms]

7kV TF field (vacuum)
Combined Shots: 29897/29900 Pol(r) and Tor(b) Flux Vs R and t

Pol. Flux [mWb/M] & Tor. Flux [mWb/M]

7kV TF Vac. Tor. Flux [mWb/M] from shell

Time [ms]
8kV, TF Relaxation CHI Discharges
Combined Shots: 29884/29886 Pol(r) and Tor(b) Flux Vs R and t

8kV TF Vac. Tor. Flux [mWb/M] from shell

Psi-inj flux
**n=1 Mode, 8kV TF, non-Relaxation CHI Sho:26070**

![Graphs and diagrams showing plasma current, outermost probe, radiated power, and toroidal flux loop over time.](image)

26070 Overview, psi-inj = 9.4 mWb, l-sb = 30 kA, Probe = 4", BT = 8kV

Plasma Current and Outermost Probe (x2000)
Shot: 26070 LP filtered Poloidal Field profiles Vs R and t

Field Strength [T]

Time [s]
Shot:26070 Fluctuation of Poloidal Flux [10^{-2}mWb]

Radius [m]

Toroidal Angle

HIT-II machine Geometry

Mode rotates c.w. and v_e is c.w.
$n=1$ Mode, $8\text{kV}$, TF Relaxation CHI Shot: 29859
Combined Shots: 29859 LP filtered Pol(r) and Tor(b) Fields Vs R and t

Field Strength [T]

Time [ms]

46th APS-DPP meeting, Savannah, Ga, Nov 15-19, 2004
Combined Shots: 29859 Pol(r) and Tor(b) Flux Vs R and t

Psi-inj flux

Pol. Flux [mWb/M] & Tor. Flux [mWb/M]

Time [ms]

0 1 2 3 4 5 6 7
CHI Magnetic Topology, Relaxation and non-Relaxation Discharges
**n=1, Rotating Mode Structure, Shot 26070**

- Reversal of poloidal field across the mode, shown in red.
- Sharp asymmetric features in the radial field are observed, in blue.
- Mode radial extent is ~5cm.
Summary and Observations

Probe effects:

- Internal probing of CHI discharges at 9cm depths have little effect on shot performance. Full depth probing, 15cm, has degraded the peak current levels by 20% but behaviour is consistent with un-probed discharges.

Relaxation Behaviour:

CHI discharges demonstrating relaxation are characterized by a recovery from the ‘Bubble Burst’ phase with a subsequent rise of plasma current, \( I_p \), and generation of poloidal flux that exceeds the injector flux. Poloidal plasma currents are produced which are paramagnetic and have reached 28% of the TF vacuum field.

- 7,8kV TF CHI discharges demonstrate fluctuating poloidal fields over the entire discharge. The more coherent the mode becomes, the more the plasma current is degraded. This is especially noticeable on shot: 29859.

- 7,8kV TF CHI discharges show an initial ‘Bubble Burst’ poloidal flux generation on level with \( \psi_{inj} \), then lowered and subsequently recovers during the ‘Relaxation period’ to levels notably higher than \( \psi_{inj} \), 50% and 30% respectively.
• 5kV TF shots show a quicker recovery from the ‘Bubble Burst’ with hardly any dip in poloidal flux. A ‘chaotic period’ of large field fluctuations begins to appear where \( \frac{\delta B_{pol}}{\delta B} \approx 1 \). The peak poloidal flux level is 100% higher than \( \psi_{inj} \).

• In 3.5kV TF shots, the ‘Bubble Burst’ phase is coincident with the chaotic period, a quiescent plasma is established until another row of the Sustainment Bank is fired. The plasma current noticeable rises at that time and some large field fluctuations seem to be associated with the change in behaviour. Poloidal flux levels reach three times higher than \( \psi_{inj} \).

• In 3kV TF shots, the bubble burst is no longer evident as it is buried in the chaotic field fluctuations which turn on earlier and persist longer than in the 3.5kV shots. The relatively quiescent phase sees the poloidal flux build slightly and the toroidal flux drop as the equilibrium adjusts. Finally, at the time of the last SB row firing, relaxation takes off again with large poloidal field fluctuations and increases in both pol and tor flux. A similar 200% poloidal flux increase over \( \psi_{inj} \) is achieved.

• Lastly, 2.5kV shots, demonstrate the same pattern three times of large poloidal fluctuations associated with a rapid build up of poloidal flux preceding quiescent periods in which the toroidal flux or poloidal plasma currents drop. The patterns are roughly initiated at the times of the SB trigger times. The poloidal flux increase is again 200% higher than \( \psi_{inj} \).
• Record $B_{\text{tor}} / B_{\text{vac,tor}}$ of 28% is achieved for the 2.5kV shots. And $I_p / I_{TF}$ reaches a peak of 80%.

• General observations on CHI shots demonstrating relaxation:

1) The magnetic axis is much more outboard than for ohmic and CHI plasmas without relaxation. The probe at 15cm insertion depth penetrates beyond the magnetic axis for most if not all shots at some time.

2) Relaxation is associated with large current fluctuations ($\delta B_{pol} / B_{pol} \approx 1$) similar to results in the SPHEX experiment. A possible explanation would be a localized toroidal current filament that is moving through the probe.

3) The consistent build up of flux to levels 200% higher than the injector flux strongly suggests that a closed flux region has been established.

4) The relaxing CHI discharges have achieved plasma currents, $I_p$, as high as record ohmic shots, but radiated power is much higher. Clearly, the perturbing effects of the probe at 15cm depth are a good indication that the plasma temperature is higher than before, also suggesting a closed flux, core plasma.
**n=1, Rotating mode, Relaxing/Non-relaxing CHI Shots:**

**Previous CHI operations:**

- Internal magnetic probing of standard 8kV TF CHI discharges showing a strong coherent n=1 mode fluctuations, have revealed a definite characteristic *‘dynamo drive’ shape* as shown in the **polar plot: Shot 26070**. The fluctuating poloidal field is asymmetric but is rotating in a sense that would drive current from the inner radius outward, i.e. to the wall. This would explain the poor performance for this mode of operation.

- Also the poloidal flux distribution shows the initial ‘Bubble Burst’ flux at the $\psi_{inj}$ level, followed by a subsequent collapse and then a build up to the same $\psi_{inj}$ level where it remains clamped throughout the duration of the discharge even though the Sustainment Bank is supplying MWs of input power.

**CHI operations Showing Relaxation:**

- Internal magnetic probing of comparable 8kV TF CHI discharges showing a strong coherent n=1 mode shows a different mode pattern. The rotating mode is not skewed from the inner radius to the outer radius as before. Therefore it would seem to contribute little to current relaxation across a separatrix. Nevertheless, the appearance of a strong coherent mode is highly correlated with a degradation in plasma current, Ip.
Future Work

- Complete the survey of CHI relaxation data: 4kV and 6kV TF discharges remain to be done.

- Continue to develop an understanding of the poloidal field generation period of these shots with regards to field fluctuations. There are more probe signals (Br, …) to consider than were discussed in this poster.
SCHEMATIC OF HIT-II DEVICE
(Magnetic Diagnostics)