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Abstract

Coaxial Helicity Injection, CHI, has been used on the National Spherical Torus Experiment (NSTX) [M. Ono et al., *Nucl. Fusion*, **40**, 557 (2000)], the Helicity Injected Torus (HIT) [B.A. Nelson et al. *Phys. Rev. Lett.,* **72**, 3666 (1994)] and HIT-II [T.R. Jarboe et al., *Phys Plasmas*, **5**, 1807 (1998)] to initiate plasma and to drive up to 400 kA of toroidal current. On HIT-II, CHI initiated discharges have been successfully coupled to ohmic sustainment [R. Raman, et al. *Phys Plasmas*, **11**, 2565 (2004)]. This paper presents the first results on the use of CHI to demonstrate the persistence of edge current drive in a pre-established single null diverted inductive discharge. Edge current drive has the potential to improve plasma stability limits [J.E. Menard et al., *Nucl. Fusion*, **37**, 595 (1997)]. While most current drive methods drive current in the interior of the plasma, CHI is well suited for driving current in the edge plasma.

The Helicity Injected Torus-II[1], HIT-II, is a spherical torus (ST) machine with capability for both conventional inductive current drive and Coaxial Helicity Injection (CHI) current drive. A diagram of the HIT-II experimental device is shown in Figure 1. As is shown in this figure, the inner and outer vessel components of the machine are electrically separated by toroidal ceramic insulators. Thus for discharges in which the scrape-off-layer (SOL) footprints rest on either vessel components of the machine, it is possible to apply electrical voltage to the flux footprints. Under appropriate conditions, using an external power supply, it should be possible to drive current along the edge, on open field lines. It has been previously postulated that under such conditions, Taylor relaxation[2] should transport some of this open field line current to the interior, and drive current along closed field lines. Others have described the use of CHI to initiate and sustain toroidal current in STs. On HIT, up to 250 kA of toroidal current was driven with CHI.[2],[3] On HIT-II, CHI initiated discharges have been coupled to ohmic discharges with a net increase in the amount of toroidal current greater than either CHI or ohmic drive alone[4]. On the National Spherical Torus Experiment, NSTX, CHI has been used to initiate and sustain 400 kA of toroidal current.[5] This paper describes the first results that show evidence for closed field line current produced as a result of driving current in the SOL of a pre-existing inductive discharge.

We first describe the experimental method used to drive edge current on open field lines. Then, theoretical requirements for driving edge current are briefly discussed. This is followed by experimental results that show consistency between experimental observations and equilibrium analysis.

In the experiments described here, the central transformer core is used to initiate a conventional inductively driven discharge. The poloidal field coils are feedback controlled on the flux loops located outside the vacuum vessel to control the plasma shape and provide the inductive loop voltage. The shape used in these experiments was a single null diverted discharge with the X-point located at the injector end of the vessel (bottom in Figure 1). The plasma was fuelled by plasma injection guns[6] located at R = 0.14 m, Z= -0.61 m. The plasma-facing wall is conditioned by Ti gettering to provide pumping of hydrogen for density control. Typical ohmic discharge parameters for this experiment are plasma current (I_p) between 80 and 150 kA, major radius (R) ~ 0.37 m, minor radius (a) ~ 0.16 m, loop voltage (V_{loop}) ~ 1.6 V, elongation (κ) ~ 1.8 and line average density (n_e) between 0.8 and 2.0 × $10^{19}/m^3$. Figure 2 is a poloidal flux plot of a typical ohmic target plasma used in these experiments from equilibrium analysis made using the EFIT[7] code. The loop voltage applied by the ohmic transformer was programmed to be constant during the period corresponding to the plasma current flattop. The CHI injector voltage was applied using up to six fast Insulated Gate Bipolar Transistor (IGBT) based H-bridge switching power amplifiers with feedback of the injector current (I_{inj}) to a prescribed demand waveform between 2 and 6 kA. Injector current is defined as the current provided by the external power supply.

It is expected that the plasma current driven by CHI will depend upon the injector current employed and on the plasma boundary conditions as follows.[4] Relaxation phenomena drive plasmas toward the Taylor minimum energy state where the force free equilibrium is given by $\nabla\times\mathbf{B} = \lambda\,\mathbf{B}$, with $\lambda = \mu_0 J/B$ a global constant, where $B = |\mathbf{B}|$ is the magnetic flux density, $J = |\mathbf{J}|$ is the current density and μ_0 is the permeability of free space. Integrating **J** and **B** over a surface with current I and flux Φ gives $\lambda = \mu_0 I/\Phi$. Helicity K $\equiv \int \mathbf{A}\cdot\mathbf{B}\, d\tau$, where **A** is the magnetic vector potential and $d\tau$ is the elemental volume. For a tokamak this is approximately the product of toroidal and poloidal fluxes, $K \sim \Phi_T \psi_p$. Thus at fixed Φ_T, $K \propto I_p$ so all current drive techniques must sustain helicity. In the case of a transformer, this is $dK/dt = 2\, V_{loop} \Phi_T$. For electrode based CHI, V_{inj} is applied to the magnetic flux, ψ_{inj}, penetrating the insulated coaxial electrodes, thus helicity is injected at the rate:

$$dK_{inj}/dt = 2\, V_{inj}\, \psi_{inj}$$

An effective loop voltage V_{eff} can be defined as the loop voltage required to obtain the same helicity injection rate:

$$V_{eff} = V_{inj}\, \psi_{inj} / \Phi_T$$

Then the efficiency $\varepsilon \equiv P_{OH}/P_{CHI} = I_p\, V_{eff} / I_{inj}\, V_{inj} = \lambda_{tok}/\lambda_{inj}$, where $\lambda_{tok} = \mu_0\, I_p / \Phi_T$ and $\lambda_{inj} = \mu_0\, I_{inj} / \psi_{inj}$.[2] Thus from an energy argument, the condition $\lambda_{inj} > \lambda_{tok}$ is required for helicity injection current drive. This assumes dissipation occurs in the tokamak and not in the injector. Dissipation in the injector lowers the efficiency.

A model by Tang and Boozer[8] explains current drive on closed flux surfaces by CHI by helical kinks in the current on open field line which produce a dynamo loop voltage on the closed field lines. This model predicts that helical modes should be observable during

CHI, however the HIT-II experiment has no diagnostic appropriate to observe such modes.

Use of the fast IGBT supplies to provide the injector current made it possible to examine the ohmic plasma both immediately before and after the application of a short pulse of CHI current drive. Figure 3 compares two discharges with different ratios of $\lambda_{inj} / \lambda_{tok}$. The injector current was ramped up in ~ 0.5 ms and turned off in < 0.1 ms. In each case, an ohmic discharge is provided for comparison. It is clear in the case where $\lambda_{inj} > \lambda_{tok}$, more toroidal current is driven and this extra CHI-driven current persists longer than is the case for $\lambda_{inj} < \lambda_{tok}$. Current flowing on open field lines will fall to zero as the applied voltage falls to zero as is seen for I_{inj}. The decay of I_p to the baseline comparison after $V_{inj} = 0$ indicates that I_p must then be on closed field lines where I_p is the total toroidal current corrected for the current flowing in the wall, I_{wall}. $I_{wall} < 5$ kA and it persists for less than 0.0002 s following the shutoff of the injector voltage. The uncertainty in I_p is 1.5% or 200 A, whichever is larger.

A comparison of the plasma parameters and EFIT analysis of shots with and without application of CHI is shown in Figure 4. Wall conditions evolved slightly between the two discharges so that the ohmic comparison shot had slightly higher density and slightly lower I_p than the CHI shot had prior to the CHI edge current pulse. The duration of the applied injector voltage was limited to ~ 1 ms to minimize the effect of the density and radiated power increases observed during the application of CHI. An increase in the electron density in the SOL during CHI is expected because the **E** x **B** drift is away from the injector. The measured toroidal plasma current corrected for toroidal wall current persists past the application of the injector current pulse with an e-folding time of ~ 0.4 ms, which is longer than the wall current decay time. The toroidal wall currents were calculated from the derivative of the flux loop signals outside the vacuum vessel, the wall geometry and the vessel resistivity. The total toroidal wall current (I_{wall}) measured in this way is < 15% of the observed increase in I_p during CHI and I_{wall} decays with an e-folding time of < 0.2 ms. It is clear from these results that I_p persists well beyond the time at which both I_{inj} and I_{wall} return to zero. This current persistence can arise only from currents flowing on closed field lines.

The decay rate of I_p after CHI is about 30 kA/ms, about four times the value observed during application of zero loop voltage at the end of an ohmic discharge with similar density. This higher dissipation indicates that the plasma current driven by CHI is in a region of higher resistivity and/or has lower inductance than the inductively driven current. This is consistent with CHI current being driven in the edge, where the plasma would become more resistive when the effect of **E** x **B** plasma drift transports colder plasma into this region from the injector electrodes. Presumably this effect could be mitigated in large machines with the capability for auxiliary heating.

In order to investigate the spatial distribution of the additional plasma current driven by CHI, analysis of the discharges was carried out using the EFIT code. This analysis did not model driven currents on open field lines and is not expected to be applicable during the period when I_{inj} is non-zero. The lack of convergence limits the period during which the EFIT analysis is available to before CHI and about 0.2 ms after CHI. The leading moment in the current distribution is the plasma internal inductance, l_i. At the earliest time following application of CHI for which I_{inj} and I_{wall} are non-zero and EFIT converges, l_i is 0.2 compared to 0.23 before CHI. This is shown in Figure 4 which indicates the current profile is broader immediately after CHI. This is consistent with the idea that adding additional current to the edge of a flat or peaked current profile should make the current profile more hollow. (The HIT-II experimentally measured surface poloidal fields show this same feature of B_p increasing more at the top and bottom than at the midplane.) A comparatively rapid decay of the plasma current in the edge and an increase in l_i as the plasma current falls after CHI is seen in Figure 4. The decay rate of I_p, dI_p/dt, in an ohmic plasma at the end of the discharge with $V_{loop} = 0$ is 7 MA/s, while immediately after CHI, dI_p/dt is 27 MA/s. The resistivity of the plasma should vary as $T_e^{-3/2}$ and the central temperature is similar in the two cases, therefore the current decay rate immediately after application of CHI is likely to be more because the persistent current is near the plasma edge in a region of lower temperature.

Thomson scattering measurements of the electron temperature and density were made for comparison of shots with and without CHI. Figure 5 shows a typical comparison. The density profile during CHI is much broader than in the ohmic case; the central n_e is about 50% greater during CHI, the density within 0.05 m from the edge increased from below the threshold for measurement (approximately $0.5 \times 10^{19}/m^3$ at 50 eV) to above the central value. The central temperature during CHI is slightly below the ohmic value, and the temperature within 0.05 m from the edge is 40 eV during CHI.

It has been demonstrated that the application of CHI during a single-null, diverted ohmic discharge can drive toroidal current that persists after the CHI drive is removed. EFIT analysis suggests that the current profile is broadened by the CHI current drive and that the current near the edge decays rapidly after CHI. Similar experiments are planned on NSTX, in this larger device with higher edge temperature, it is expected that the CHI driven current will persist longer.

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Figure Captions:

Figure 1. Schematic drawing of an R-Z plane cut of the Helicity Injected Torus, HIT-II experiment.

Figure 2. EFIT flux surface reconstruction of ohmically driven target for CHI edge drive (pulse 29273 at 16 ms).

Figure 3. Injector voltage, injector λ, tokamak λ, injector current, and plasma current for two levels of CHI edge drive, $\lambda_{inj} < \lambda_{tok}$ (left) and $\lambda_{inj} > \lambda_{tok}$ (right). For each case, a reference ohmic only discharge is shown.

Figure 4. Injector current, plasma current, vessel wall current, and internal inductance for a $\lambda_{inj} > \lambda_{tok}$ discharge. Note both the persistence of toroidal plasma current after the injector and wall currents are both zero and the drop in l_i that indicates a broader current profile after CHI.

Figure 5. Multi-point Thomson scattering T_e and n_e data for CHI edge drive (left) and ohmic only (right).

FIGURE 1

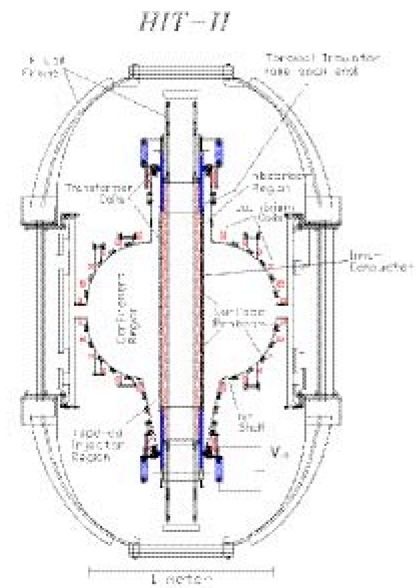


FIGURE 2

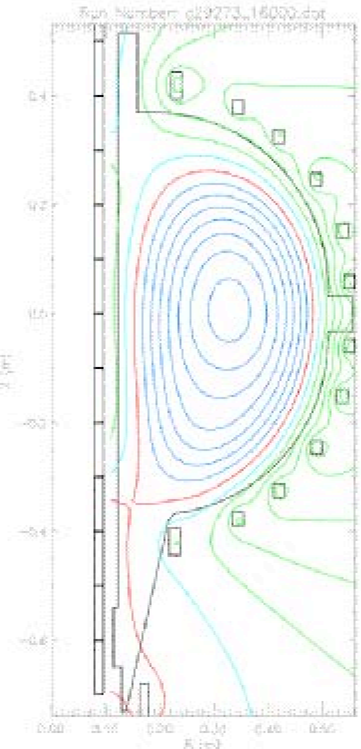


FIGURE 3

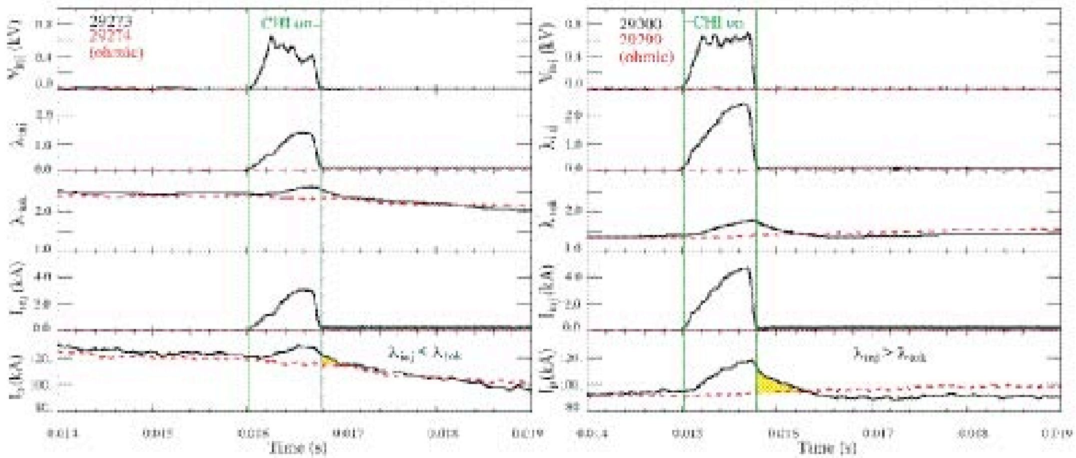


FIGURE 4

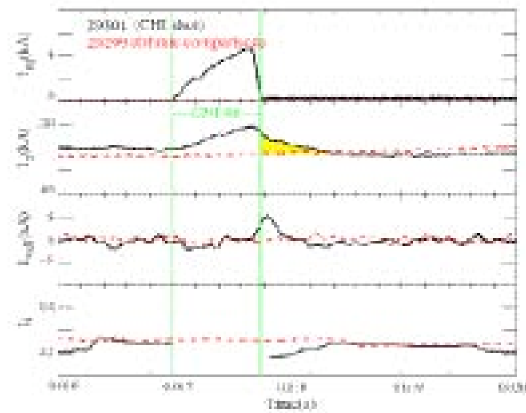
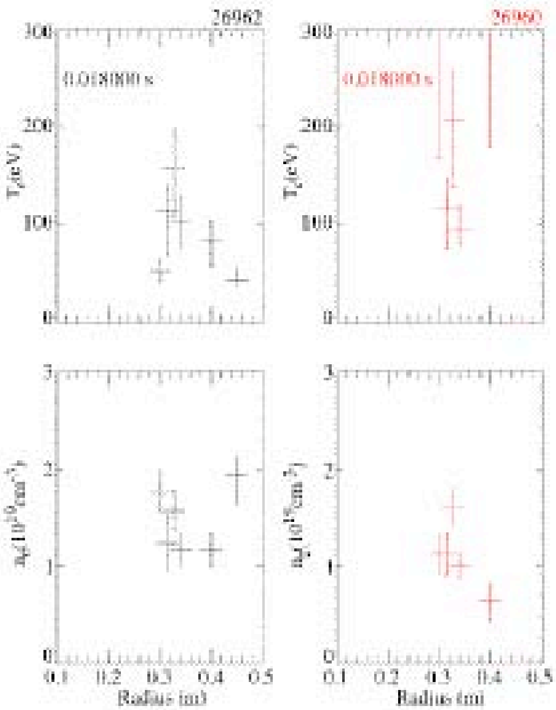


FIGURE 5



26962
26960
0.018000 s
0.018000 s
T_e(eV)
T_e(eV)
n_e(10^{19}cm^{-3})
n_e(10^{19}cm^{-3})
Radius (m)
Radius (m)

[1] T.R. Jarboe, M.A. Bonnet, A.T. Mattick, et al., *Phys. Plasmas*, **5**, 1807 (1998).

[2] B.A. Nelson, T. R. Jarboe, A. K. Martin, D. J. Orvis, J. Xie, C. Zhang, L. Zhou, *Phys. Plasmas,* **2**, 2337 (1995).

[3] B.A. Nelson, T.R. Jarboe, D.J. Orvis, L.A. McCullough, J. Xie, and L. Zhou, *Phys. Rev. Lett.*, **72**, 3666 (1994).

[4] R. Raman, T.R. Jarboe, B.A. Nelson, et al., *Phys. of Plasmas*, **11**, 2565 (2004).

[5] T.R. Jarboe, R. Raman, B.A. Nelson, et al., "Progress with helicity injection current drive," Fusion Energy 2002 (Proc. 19th. Int. Conf. Lyon, 2002) (Vienna: IAEA) CD-ROM file IC/P-10 and
http://www.iaea.org/programmes/ripc/physics/fec2002/html/fec2002.htm

[6] D. J. Den Hartog, D. J. Craig, G. Fiksel, and J. S. Sarff, *Plasma Sources Science and Technology*, **6**, 492 (1997).

[7] L.L. Lao et al., *Nucl. Fusion*, **25**, 1611 (1985).

[8] X.Z. Tang and A.H. Boozer, *Phys. Plasmas*, **11**, 2679 (2004).

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