# Evidence for Separatrix Formation and Sustainment with Steady Inductive Helicity Injection

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# Evidence for Separatrix Formation and Sustainment with Steady Inductive Helicity Injection

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Abstract: The first sustainment of toroidal plasma current of 50 kA at up to 3 times the injected currents, added in quadrature, using steady inductive helicity injection is described. Separatrix currents—currents not linking the helicity injectors—are sustained up to 40 kA. Decreases in the n = 1 toroidal mode of the poloidal magnetic field at higher current amplifications indicate more quiescent, direct toroidal current drive. Results are achieved in HIT-SI (with a spheromak of major radius 0.3 m) during deuterium operations immediately after helium operation. These results represent a breakthrough in the development of this new current drive method for magnetic confinement fusion.

Improvements in current drive efficiencies are needed to lower the circulating power fraction to meet the requirements of a magnetic confinement fusion reactor [1, 2, 3]. Helicity injection, driving the bulk electron distribution, provides an alternative path for reducing the circulating power. Electrode based helicity injection has been used for spheromak formation [4] and is an effective method for the startup of toroidal devices [5, 6, 7]. Steady Inductive Helicity Injection (SIHI) requires less density injection [8] and should have less impurity generation than electrode based methods. SIHI involves the non-linear plasma phenomena of self-organization, relaxation and reconnection that are of general interest in the study of planetary and solar magnetic fields. Magnetic helicity is the linkage of magnetic flux with magnetic flux [9]. Helicity is conserved on magnetic energy time scales and has been shown to be the best constant of motion in a magnetized plasma [4]. Spheromak formation relies on the relaxation of the magnetic field structure towards a Taylor state [10]. The Helicity Injected Torus with Steady Inductive Helicity Injection (HIT-SI) [11] investigates a method of current drive and spheromak formation through constant inductive helicity injection into a confinement volume of major radius 0.3 m. Magnetic helicity is injected into HIT-SI through the use of two injectors, named the X- and Y-injectors, each operating with injected voltage and flux in phase to inductively drive current along field lines [11, 12, 13]. For a more detailed description of the construction and operation of HIT-SI see Reference 12. The results presented here have been achieved with the injector voltage and flux driven sinusoidally at 14.5 kHz. A principal goal of the HIT-SI experiment is to prove the efficacy of inductive helicity injection current drive by forming and sustaining a spheromak with significant toroidal current.

Wall conditioning with helium plasmas and subsequent operation with deuterium has led to improved performance and new insights into the current drive mechanism. This is the first time to the authors' knowledge that helium has been used to condition the alumina walls of a magnetic confinement device. Deuterium discharges have achieved HIT-SI record toroidal currents (> 50 kA) and current amplification ratios (3, the record for all spheromaks) with up to 40 kA of separatrix current (see Reference 11 Figure 2 showing the spheromak equilibrium with separatrix). Additionally, the measured n = 1 toroidal

Fourier mode of the poloidal magnetic field decreases at higher current amplification ratios indicating more direct drive of the toroidal current.

An FIR interferometer [14] is used to measure the chord-averaged electron density at an impact parameter of 35 cm along the midplane of the confinement volume. Surface probes measure the poloidal magnetic field at 18 locations around each of four poloidal cross sections located at toroidal angles of 0°, 45°, 180° and 225°. Using the surface probes and the assumption of zero magnetic field at the corners in the poloidal cross section (two poloidal cross sections are shown in Figure 1), Amperian loops are constructed to measure the toroidal current (the simply-connected confinement volume precludes the use of an external Rogowski coil for this measurement). The toroidal current reported in this paper is the average toroidal current from these four locations [15, 16]. Both injector currents are measured with Rogowski coils. The toroidal current and the injector currents added in quadrature (quadrature values are the square root of the sum of the squares of injector signals averaged over an injector cycle) are accurate to within 5%. The $n = 1$ Fourier mode amplitude and phase are measured by surface magnetic probes located at 16 locations on both sides ($z = +/- 3$ cm) of the midplane diagnostic gap. SPRED (Spectroscopy, Poor Resolution Extended Domain) measures line radiation in HIT-SI at an impact parameter of 29 cm along the midplane of the confinement volume.

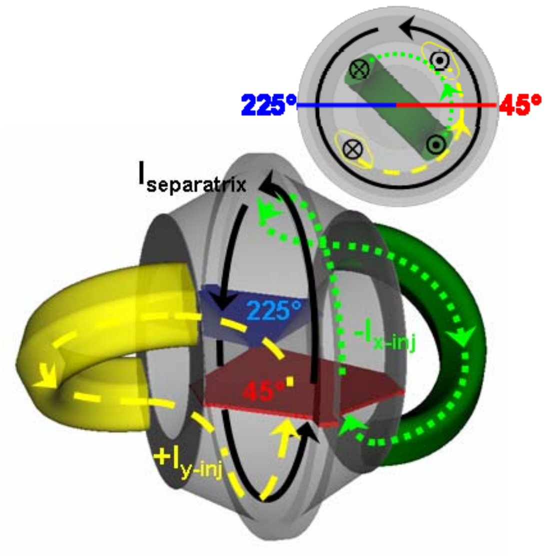


**Figure 1: The HIT-SI geometry is shown with the confinement volume outlined in gray, the Y-injector in yellow and the X-injector in green. The poloidal cross sections at 45° and 225° degrees are in red and blue respectively. Included in the figure is a model representing the current paths in HIT-SI. The separatrix current (black) is shown with the injector currents at a time with negative X-injector (green) and Y-injector (yellow) current. In the top-right of the figure is a 2-D projection of the current paths with the view looking at the X-injector from the midplane of the confinement volume. At the representative time shown the X-injector, Y-injector and separatrix current pass the 45° plane, while only the separatrix current passes the 225° plane.**

Careful attention to fueling and wall conditioning are necessary to produce the desired plasma conditions in magnetic confinement fusion experiments [17]. HIT-SI uses alumina as a plasma-facing surface to insulate the plasma from the copper flux conserver and ensure that current drive is completely inductive [12]. Alumina reacts chemically with hydrogen isotopes, which makes it a good pump. However, the walls quickly become saturated with hydrogen isotopes, increasing wall recycling and radiated power. Past experimental results on HIT-SI have used helium as the operating gas [8, 11, 12, 13]. Earlier experiments performed in hydrogen and deuterium without helium conditioning had achieved low toroidal currents. Recent operations have shown that helium can be used to condition the walls before deuterium operations. For the data presented in this paper, gas is injected through needle valves at the toroidal midpoint of the two injector half toroids. Plasma breakdown is achieved spontaneously from the injector voltage. Without helium wall conditioning, adequate fueling of the injectors excessively fuels the confinement volume resulting in poor achieved toroidal current. Gas deficiencies in the injectors cause voltage spikes and localized wall heating near the injector mouths. The potential for localized wall heating limits the shot length to 2 ms. Helium wall conditioning allows higher gas injection rates while still achieving lower density in the confinement volume through the pumping of deuterium by the alumina walls.

Three shots of a typical helium and deuterium shot sequence are shown in Figure 2 and Figure 3. Operating settings are similar for all three shots. The first shot is a typical helium shot with an average electron density of ~$4 \times 10^{19}$ $m^{-3}$ and a toroidal current of magnitude 20 kA (toroidal current polarity is not controllable for dual injector shots [13]). For the first deuterium shot, the toroidal current reaches 40 kA with lower electron density than the helium shot. The total injected power on this deuterium shot is ~25% higher than the helium shot despite the similar operating settings. Higher plasma impedance, from the lower density, causes a larger increase in injected voltage compared to the decrease in injected current resulting in increased power injection. Continued deuterium operations lead to increased density and an oscillating toroidal current of lower magnitude. A large increase in impurity hydroxide radiation occurs after repeated deuterium shots as the walls no longer pump the deuterium (see Figure 3).

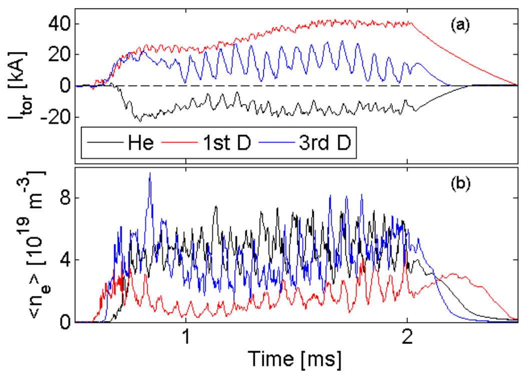


**Figure 2: (a) The toroidal currents and (b) line-averaged electron densities of a helium shot (121959) and subsequent deuterium shots (121961 and 121963).**

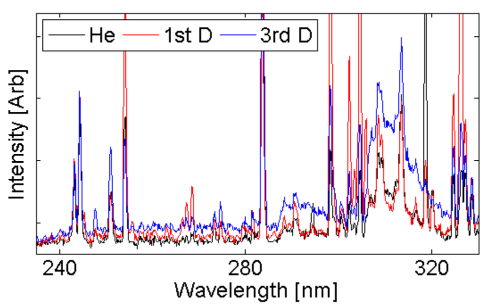


**Figure 3: Line radiation of a helium shot (121959) and subsequent deuterium shots (121961 and 121963).**

The toroidal current amplification is calculated by dividing the toroidal current time-averaged over an injector cycle by the injector currents added in quadrature. Part d) of Figure 4 shows current amplification greater than 2 achieved from 1.1 ms until the injectors are shut off at 1.8 ms with peak amplification during injector drive of 3. The quadrature $\lambda_{inj}$ is 21 $m^{-1}$ at peak amplification. Also of note is the time between 0.9 and 1.5 ms when the toroidal current rises from ~20 to ~50 kA. This is the first time on HIT-SI that the toroidal current has shown steady growth through multiple injector cycles to a current amplification greater than 2. This result provides important experimental confirmation of the ability of SIHI to continuously build up toroidal current during the sustainment of the plasma discharge.

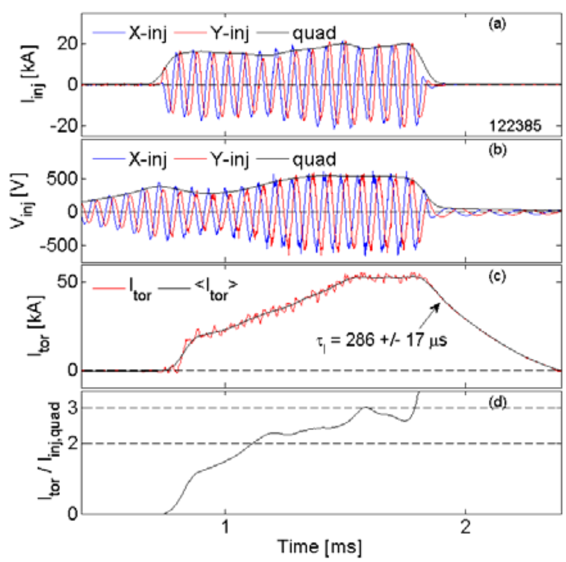


**Figure 4: X- and Y-injector currents (a) and voltages (b) with quadrature values, c) Toroidal current and toroidal current time-averaged over an injector cycle. The current decay time, $\tau_I = -I/(dI/dt)$, is averaged over 100 μs after the injectors are off, d) Current amplification of the time-averaged signals.**

The average and oscillation magnitude of the local toroidal currents are roughly the same at each toroidal location (see Figure 5). Oscillations in the local toroidal currents are at the injector frequency (14.5 kHz). The separatrix current ($I_{sep}$) is calculated by subtracting the average of the instantaneous amplitude of the local current oscillations at the four toroidal locations from the average toroidal current. After the injectors turn off the separatrix current increases as the helicity in the injectors is transferred, through magnetic relaxation, to the separatrix current.

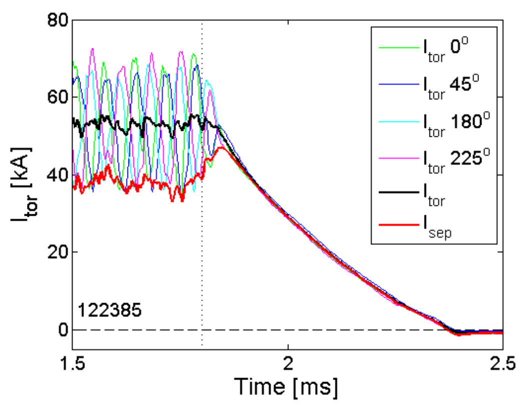


**Figure 5: Toroidal current measurements at the four toroidal locations with the average toroidal current and the separatrix current. The vertical dotted line at 1.8 ms indicates the time when the injectors are turned off.**

Using toroidal Fourier mode analysis of the poloidal magnetic fields measured by the surface probes, the injector magnetic fields appear predominantly as an n = 1 mode. In addition to the injector n = 1 mode there are n = 1 eigenmodes of the confinement volume. The magnitude of the n = 1 Fourier mode measured by the surface probes increases before axisymmetric toroidal current is measured in the confinement volume (see Figure 6). As the toroidal current increases the n = 1 mode decreases. The amplitude of the injected current is relatively constant during the shot. This implies the decrease in the measured n = 1 Fourier mode is the result of less energy in the n = 1 eigenmode of the confinement volume. It is proposed that as the toroidal current increases the injectors begin to transfer helicity directly to the toroidal current (perhaps through electron locking [8]) without driving the n = 1 eigenmode of the confinement volume. The inverse correlation of toroidal current with measured n = 1 Fourier mode for six deuterium shots is summarized in Figure 7.

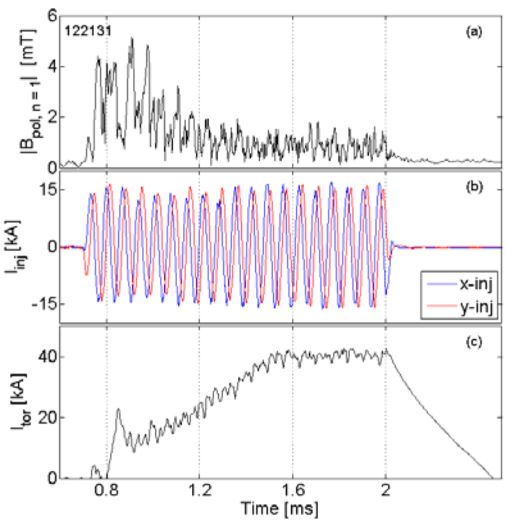


**Figure 6: (a) The magnitude of the n = 1 toroidal Fourier mode of the poloidal magnetic field, (b) the injector currents and (c) the toroidal current.**

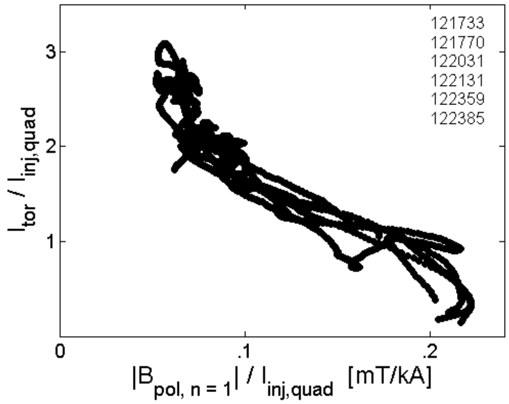


**Figure 7: Scatter plot of the current amplification compared to the magnitude of the n = 1 toroidal mode of the poloidal magnetic field averaged over an injector cycle and normalized by the quadrature injector signal for six shots.**

The local toroidal current measurements can be explained by a separatrix current along with injector currents (see Figure 1). When the average toroidal current is greater than the total injected current, all of the current in the confinement volume will flow in the same toroidal direction (the injector currents will flow in the same direction as the separatrix current). The oscillations in the locally measured currents are from the oscillating injector currents passing that location. This interpretation is confirmed by the magnitude and phase of the measured current oscillations shown in Figure 5. The minima in the local current measurements occur when no injector current passes a given toroidal location and therefore measures only separatrix current. Thus, the minimum level of toroidal current at each of the four toroidal locations is attributed to the current inside the separatrix (Figure 5) with the oscillations the result of the injector currents passing by a given toroidal location. This result indicates a sustained region of separatrix current through multiple injector cycles.

An alternative explanation for the current amplification is injector current making multiple toroidal passes in the confinement volume. This explanation also requires the injector currents to transit in the same toroidal direction of the confinement volume each half cycle. The toroidal current would then be scaled by the sum of the injector current magnitudes, which has significant fourth harmonic content. At current amplifications greater than 2 the magnitude of this fourth harmonic content is approximately half of the magnitude of the first harmonic. The local toroidal current measurements do not suggest the presence of large oscillations at four times the injector frequency (see Figure 5). In addition, each injector turns off every half cycle, forcing closure of the injector flux. It seems unlikely that every half cycle injector field lines making multiple toroidal transits would be produced or handed off to the other injector. However, the data do not preclude some injector current making multiple toroidal passes so the amount of separatrix current is qualified by the phrase "up to."

The efficiency of SIHI is calculated by comparing the Ohmic power required to maintain the current ($P_\Omega$) to the input power from the injectors ($P_{inj}$) [18]. Between 1.5 and 1.8 ms of shot 122385 (Figure 4 and Figure 5), the toroidal current and input power are nearly constant: $\overline{I_{tor}} = 53\,\text{kA}$, $\overline{I_{sep}} = 38\,\text{kA}$ and $\overline{P_{inj}} = 9.4\,\text{MW}$. The toroidal current energy, $W_{I_{tor}} = 420\,\text{J}$ [19], is used to estimate the energy in the separatrix region,

$W_{sep} = W_{I_{tor}} \cdot I_{sep} / I_{tor} = 300$ J. Since $W_{I_{tor}} \propto I_{tor}{}^2$ the energy decay time can be calculated from the current decay time (Figure 4), $\tau_W = \tau_I / 2 = 143 \pm 9 \mu s$. This gives $P_\Omega = W_{sep} / \tau_W = 2.1 \pm 0.1$ MW and an efficiency of $\epsilon = P_\Omega / P_{inj} = 0.22 \pm 0.01$. Direct comparisons of the current drive efficiencies of helicity injection to conventional current drive methods are limited by the accuracy of scaling laws. Further experiments are necessary to test the favorable scalability of helicity injection to reactor conditions [20].

Achieving the record current amplification for a spheromak of 3 with current persistence after the injectors are off proves that SIHI is an effective solenoid free and electrode free plasma startup method. This in itself is a major breakthrough for fusion power generation. The evidence presented here for significant separatrix sustainment and the monotonically increasing toroidal current to higher current amplifications shows the viability of SIHI current drive. Additionally, as the current amplification improves the injectors demonstrate more effective coupling to the toroidal current without exciting the n = 1 eigenmode of the confinement volume, indicating SIHI may be compatible with good confinement. It is suggested that toroidal current drive is limited by a buildup of density in the confinement volume.

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[1] J. Pamela *et al.*, Fusion Eng. Des. **84**, 194 (2009)

[2] H. Zohm, Fusion Sci. and Technol. **58**, 613 (2010)

[3] N.J. Fisch, J. Plasma Phys. 76, 627 (2010)

[4] T.R. Jarboe, Plasma Phys. Controlled Fusion **36**, 945 (1994)

[5] R. Raman *et al.*, Phys. Rev. Lett. **104**, 095003 (2010)

[6] M. Ono *et al.*, Phys. Rev. Lett. **59**, 2165 (1987)

[7] B.A. Nelson *et al.*, Phys. Rev. Lett. **72**, 3666 (1994)

[8] T.R. Jarboe *et al.*, Nucl. Fusion **51**, 063029 (2011)

[9] H.K. Moffatt, *Magnetic Field Generation in Electrically Conducting Fluids* (Cambridge University Press, Cambridge, 1978)

[10] J.B. Taylor, Rev. Mod. Phys. **58,** 741 (1986)

[11] T.R. Jarboe *et al.*, Phys. Rev. Lett. **97**, 115003 (2006)

[12] P.E. Sieck *et al.*, Nucl. Fusion **46**, 254 (2006)

[13] D.A. Ennis *et al.*, Nucl. Fusion **50**, 072001 (2010)

[14] R.G. O'Neill *et al.*, Fusion Energy **26**, 131 (2006)

[15] P.E. Sieck *et al.*, IEEE Trans. Plasma Sci. **33**, 723 (2005)

[16] J.S. Wrobel, *Ph.D. thesis* (University of Washington, Seattle, 2011)

[17] J. Winter, Plasma Phys. Controlled Fusion **38**, 1503 (1996)

[18] A.H. Boozer, Phys. Fluids **31**, 591 (1988)

[19] R.G. O'Neill, Phys. Plasmas **14**, 112304 (2007)

[20] N.J. Fisch, Rev. Mod. Phys. **59**, 1 (1987)