Evidence for Separatrix Formation and Sustainment with Steady Inductive Helicity Injection


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Abstract

The Helicity Injected Torus with Steady Inductive Helicity Injection (HIT-SI) has achieved a breakthrough in the development of a new, more efficient current drive method for magnetic confinement fusion. Results include the first sustainment of toroidal plasma current of over 50 kA at current amplifications ($I_{tor}/I_{inj}$) of up to 3. Separatrix toroidal currents—currents not linking the helicity injectors—are sustained at up to 40 kA. The improved toroidal current growth is a result of better density control during deuterium plasmas with the ratio of current density to electron density ($j/n$) exceeding the Greenwald limit of $10^{-14}$ Am. High performance discharges ($I_{tor}/I_{inj} > 2$) are characterized by a decrease in the $n = 1$ mode activity measured by surface probes near the midplane of the confinement volume. Suppression of internal magnetic fields (measured by an internal probe) below the predicted Taylor equilibrium is indicative of plasma pressure and a region of plasma separate from the injector flux.

Introduction

The need for sustained, efficient current drive in toroidal magnetic confinement fusion devices is a broad and open topic in fusion research [1]. HIT-SI [2] accomplishes helicity injection current drive on a spheromak of major radius 0.3 m. Magnetic helicity is the linkage of magnetic flux with magnetic flux [3]. Two injectors, named the X- and Y-injectors, operate with voltage and flux circuits in phase to inductively drive current along field lines [4, 5]. For the data presented here the injector circuits are driven sinusoidally at 14.5 kHz.

Ratio of current density to electron density ($j/n$)

Spheromaks and Reversed Field Pinches (RFP) become radiation dominated at higher plasma densities [6]. Past experiments on HIT-SI have been unable to achieve ratios of current density to electron density ($j/n$) above $10^{-14}$ Am [7]. The recent results presented here are achieved in HIT-SI during deuterium operations immediately after helium operation [8]. The helium operation cleans the alumina walls, which then act to pump the deuterium. This process has produced the first HIT-SI plasmas with $j/n > 10^{-14}$ Am. For similar injector operating conditions, deuterium shots achieve improved toroidal current growth at lower electron densities than helium shots (see Figure 1). This deuterium shot has more than a sevenfold improvement in peak $j/n$ compared to the helium shot.

A key to operating HIT-SI is to fuel the injectors without overfueling the confinement volume. At too low of fueling rates the injectors become gas starved. When the injectors become gas starved the injected voltage increases to increase the injector current. This voltage increase can exceed the limits of our circuit causing a fault to trip. Additionally, shots with high power and low fueling rates tend to have problems with localized wall heating near the injector mouths. This wall heating is a key limiter of the shot length. Wall pumping of deuterium by alumina allows for higher fueling rates in the injectors while achieving lower density in the confinement volume. It is suggested that the toroidal current drive at the end of the shot is limited by a buildup of density in the confinement volume.
n = 1 mode activity for high performance deuterium shots

High performance deuterium shots show a difference in the n = 1 mode behavior. The n = 1 mode is calculated using Fourier analysis of the poloidal magnetic fields measured by the surface probes [9]. At the beginning of a typical shot (see Figure 2) a large magnetic eigenstate having n = 1 symmetry like the injectors is produced. This increased n = 1 mode activity is measured before any toroidal current is measured. The eigenstate then makes a rapid transition to produce a weak toroidal current (at ~0.8 ms in the bottom of Figure 2) that the injectors begin building up with considerable n = 1 activity. As the toroidal current grows the n = 1 activity decreases while the helicity injection rate remains nearly constant (Figure 3), indicating an evolution to a more quiescent, direct current drive. A persistent toroidal current is needed to provide the magnetic topology for the injectors to couple to.
**Internal magnetic field comparison to Taylor equilibrium**

The internal magnetic fields for high performance deuterium shots are suppressed from the fields predicted by the zero pressure, constant $\lambda$, Taylor equilibrium (Figure 4 and Figure 6). The Taylor equilibria in HIT-SI are generated by the superposition of the Taylor states [10] for the confinement volume (scaled by the toroidal current measured by the surface probes) and each injector (scaled by Rogowski measurements of each injector current) using a constant $\lambda = 10.3$ m$^{-1}$. Past results on HIT-SI [2] and present low current amplification shots (Figure 5 and Figure 7) show good agreement between the internal magnetic fields and the Taylor equilibrium.

![Figure 4: Comparison of the internal poloidal magnetic probe signals (black) to the fields predicted by the Taylor equilibrium reconstruction (red) at five locations for a deuterium shot with current amplification reaching 3 at 1.6 ms. The bottom trace is near the magnetic axis and the top trace is near the wall with the 0 of each successive probe shifted up by 40 mT.](image)

![Figure 5: Comparison of the internal poloidal magnetic probe signals (black) to the fields predicted by the Taylor equilibrium reconstruction (red) at five locations for a helium shot with peak current amplification of 1.4. The bottom trace is near the magnetic axis and the top trace is near the wall with the 0 of each successive probe shifted up by 40 mT.](image)

The poloidal field measured by the internal probe near the wall (top trace of Figure 4) agrees well with the predicted Taylor equilibrium. Both the poloidal (Figure 4) and toroidal (Figure 6) fields show lower measured DC fields than predicted by the Taylor equilibrium. This diamagnetic effect is indicative of plasma pressure and a region of plasma separate from the injector flux. The amount of toroidal current in the region of plasma separate from the injector flux, named separatrix current, can be bounded by the minimum toroidal current measured at each of the four Amperian loops constructed by the surface probes. This minimum current persists through multiple injector cycles and bounds the separatrix current at 40 kA (see Figure 5 of Reference 8).
Conclusion

Increasing the ratio of current density to electron density \((j/n)\) through wall conditioning with helium plasmas and operating with deuterium led to improved performance. The change in mode activity at higher current ratios indicates a symmetric magnetic topology that is sustained and coupled to by the injector drive. In addition, the internal probe measurements indicate plasma pressure during injector drive.

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