Current Drive Experiments on the HIT-II Spherical Torus

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Abstract

This paper describes the following new achievements from the Helicity Injected Torus (HIT) program: a) formation and sustainment of a toroidal magnetic equilibrium using coaxial helicity injection (CHI) in a conducting shell that has an L/R time much shorter than the pulse length; b) static formation of a spherical torus with plasma current over 180 kA using a transformer and feedback controlled equilibrium coils; and c) production of a current increase in a transformer produced spherical torus using CHI.

The purpose of the HIT program is to study and develop helicity injection current drive for magnetic confinement.[1-3] A fusion reactor requires an efficient method of steady-state current drive. Current drive methods involving neutral beams and radio frequency waves have efficiencies as low as 0.1% when scaled to a reactor.[4,5] Current drive by CHI has predicted reactor efficiencies in the tens of percent [1] reducing the dominance of the cost of current drive in a reactor to insignificance. The HIT experiment was motivated by the success of CHI current drive on spheromaks [6] and by helicity injection current drive on reversed field pinches [7] and tokamaks.[8] The HIT experiment was a low aspect ratio tokamak with major radius 0.3 m, minor radius 0.2 m, and elongation 1.75. Only CHI was used to form and sustain the tokamak where currents as high as 250 kA and electron temperatures as high as 100 eV were achieved at densities of $3\text{-}10\times10^{19}$ m^{-3}. External equilibrium and stability currents were provided passively by a 10 mm thick copper shell flux Conserver.

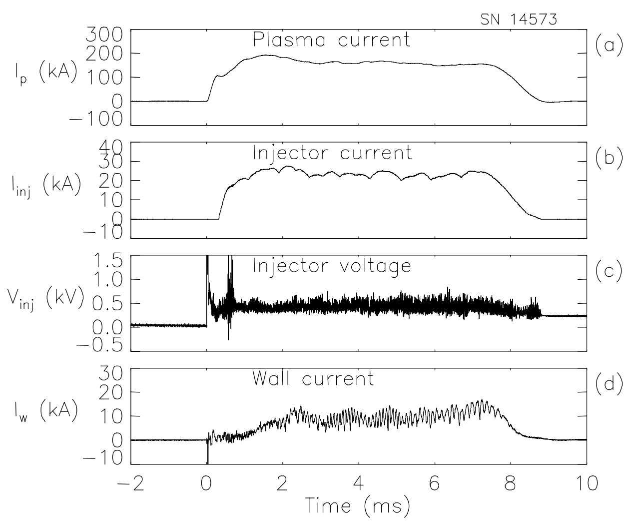


Figure 1. a) Plasma current, b) injector current, c) injector voltage, and d) wall current using only CHI on HIT-II.

The results reported here are from the HIT-II experiment, which has the same geometry as HIT. The 10 mm thick copper outer shell and 12 mm thick copper central conductor of HIT are replaced by a 6 mm thick 304 stainless steel shell (L/R=1.2ms) and a 3.5 mm thick 304 stainless steel central conductor. The central conductor is covered with a 12 mm thick graphite [Union Carbide type ATJ] cylinder. A feedback controlled coil set provides equilibrium fields and also transformer action.[3] CHI experiments on HIT-II have been conducted in flux configurations similar to the previous HIT device, the upcoming NSTX device, and the CHI experiment on DIII-D. The best results to date have been obtained with the NSTX configuration, with a peak current of 200 kA with 150 kA sustained for 5 ms. The longest sustained operation is shown in Figure 1 with 150 kA of plasma current for 7 ms (power supply limited), similar to the long pulse discharge on HIT[2] where the shell L/R time was about 70 times longer. The n=1 oscillations seen in HIT[2,3] are also seen in HIT-II (see Figure 1d), demonstrating that the thin shell is adequate for limiting the growth of the n=1. The oscillations seen in figure 1d are due to the n=1. Modes that lock to the thin wall have not been observed. Limiter and divertor Ohmic discharges have been produced with plasma currents in excess of 190 kA.

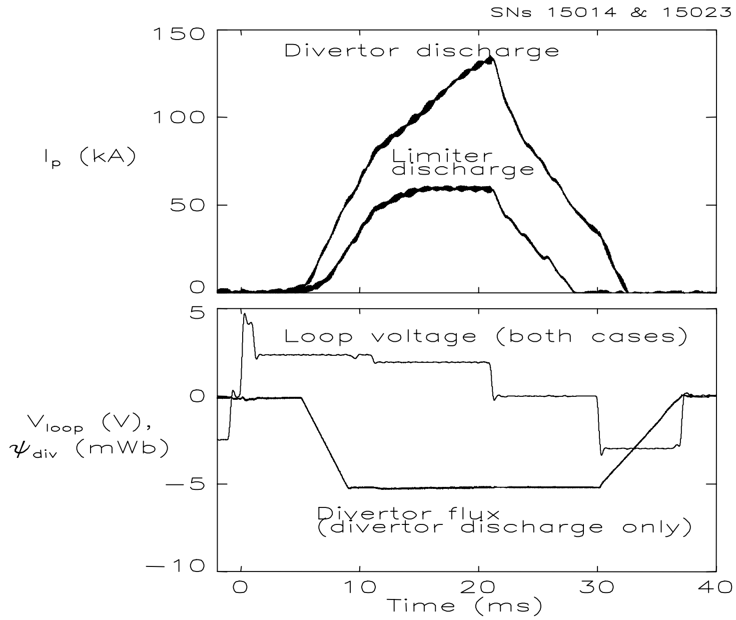
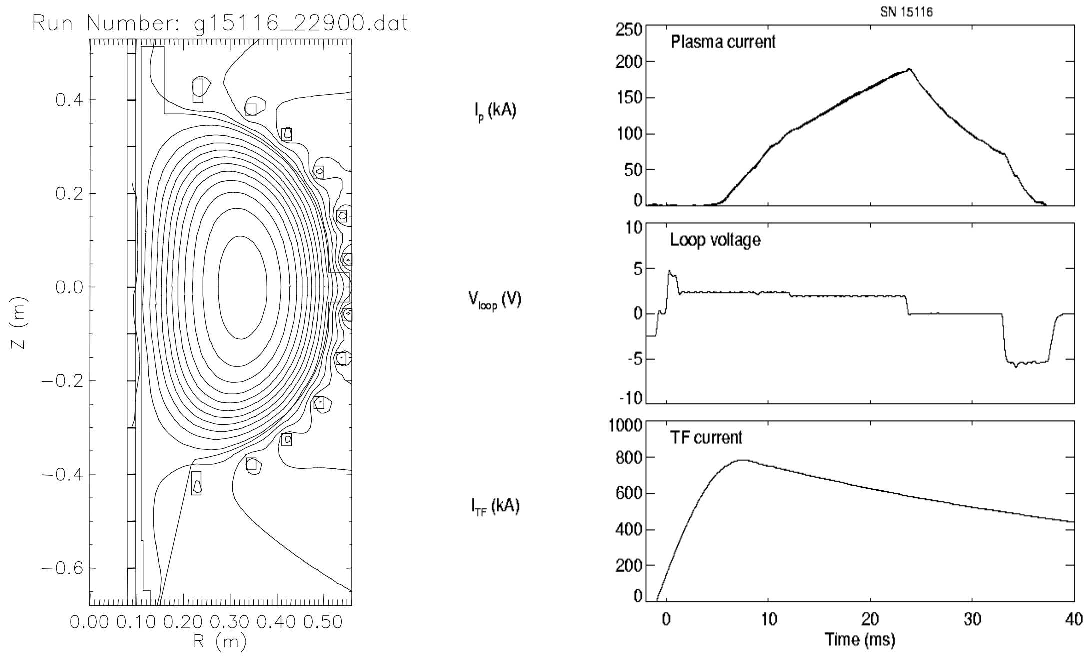


Figure 2. Transformer only data on HIT-II. The top two curves are the toroidal plasma current vs. time for an NSTX like divertor and a limiter discharge. The bottom two traces are the loop voltage for both conditions and the divertor flux in the divertor case.

Figure 2 shows the loop voltage vs. time, 4 V for the first ms, then 2.25 V for 10 ms and 1.85 V for the final 10 ms. The higher initial loop voltage assists in early plasma formation. For limiter discharges, the second ramp increases the plasma current to about the 60 kA level and the final ramp maintains the current for 5 ms. If the loop voltage during the final 10 ms is also 2.25 V, the plasma current reaches 130 kA. For divertor discharges, the current continues to increase even with the 1.85 V. At zero loop voltage the current decreases at about 10 kA/ms. He glow discharge cleaning between discharges is needed to obtain Ohmic as well as reproducible discharges. The irregular behavior in the decay at times before the 30 ms is caused by internal reconnection events (IRE) first observed in START.[9] The modulation of the thickness of the plasma current curve between 10 ms and 20 ms is caused by the pulse width modulation method of feedback control with baseline subtraction and is not a real signal. For divertor discharges, the CHI electrodes act as the divertor plates and the coils near the injector produce a CHI flux configuration. All the coils undergo the flux swing. Occasional bursts of H**.** emission are observed, probably due to diverted plasma striking the walls. Increasing the vertical field allows currents of over 180 kA, as shown in Figure 3. (The “divertor” case in figure 2 also has more vertical field, possibly contributing to the better performance.)



(a) (b)

Figure 3. a) EFIT equilibrium near maximum current, and b) plasma current, toroidal field current, and loop voltage vs. time for one of the highest current discharges on HIT-II. Only transformer action is used with a 50 mVs flux-swing. The closed poloidal flux is calculated to be 28mWb. The toroidal field current is the same for all discharges discussed in this paper.

The flux contour plot is also shown for a time near the peak of the current. Even for this transformer driven plasma, preliminary EFIT equilibria show a hollow current profile with $l_i = 0.36$ that is flatter than with CHI ($l_i = 0.11$).[6] The time for the discharge may not be long enough for the peaked current profile to evolve, or another possibility is that the much higher toroidal electric field near the central column may maintain a hollow current profile in the ST.

A primary motivation for CHI is to drive steady state current after the volt-seconds in the Ohmic transformer are depleted. Figure 4 shows data from such a discharge. A limited Ohmic discharge is run from 0 to 8 ms then an NSTX-like divertor flux is added. At t = 17 ms, the divertor flux is fully established while the Ohmic current drive is terminated. CHI current drive is then applied. The initial 50 kA of Ohmic current is increased to over 100 kA and the discharge is further sustained for the 7 ms duration of the CHI discharge.

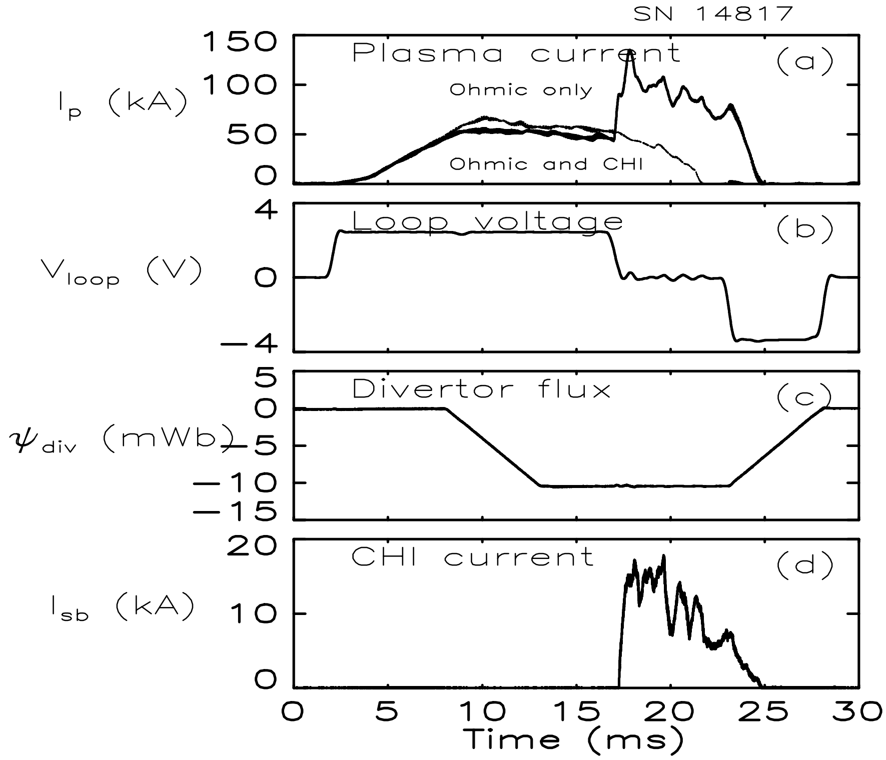


Figure 4. Demonstration of the addition of a CHI discharge to an Ohmically generated plasma. a) Plasma current, b) transformer loop voltage, c) divertor flux, and d) CHI injector current.

In the future we plan to measure the temperature, density, and confinement times of HIT-II plasmas. The effects of CHI on spherical torus confinement will be studied. The use of CHI in concert with transformer current drive for profile control and longer steady-state sustainment times will be further developed.

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