Progress with Helicity Injection Current Drive

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Abstract: Coaxial Helicity Injection (CHI) experiments in the NSTX and HIT–II devices are reported. NSTX has produced toroidal currents of 0.4 MA and pulse lengths of up to 0.33 s. These discharges nearly fill the NSTX main chamber, and show the n=1 rotating distortion characteristic of high-performance CHI plasmas. CHI has been used in HIT–II to provide a closed flux startup plasma for inductive drive. The CHI startup method saves transformer volt-seconds and greatly improves reproducibility and reliability of inductively driven discharges, even in the presence of diminishing wall conditions.

1. Introduction

The Spherical Torus (ST) is a magnetic confinement concept having the advantages of high beta and a projected high fraction of bootstrap current drive [1]. The favorable properties of the ST arise from its low aspect ratio, which leaves very restricted space for a central solenoid to induce the toroidal current. This makes sustained non-inductive operation necessary for the success of the ST concept. Coaxial Helicity Injection (CHI) is a promising candidate for initial plasma generation and for edge current drive during the sustained phase [2,3].

CHI drives current initially on divertor (or "injector") flux having strike points on two coaxial electrodes. (The injector flux is defined as the difference in poloidal flux between the upper and lower insulating gaps that separate the inner and outer electrodes.) This current pushes the injector flux outward into the main chamber, creating a current density profile that is hollow and intrinsically unstable. Taylor relaxation predicts a flattening of this current profile through a process of magnetic reconnection leading to current being driven throughout the volume, including closed field lines. Such current penetration to the interior is eventually needed to provide CHI sustainment current during the long pulse non-inductive phase.

Although an ST reactor is not expected to have a central solenoid, demonstration of the capability to hand-off a CHI produced plasma for inductive operation is a near-term objective of the NSTX program. Such a demonstration implies that in the future, after sustained non-inductive current drive methods have been developed on an ST, CHI produced plasmas could be directly handed-off to these systems.

CHI has been used in the NSTX experiment to produce toroidal plasma currents, I_p ~ 0.4 MA, for pulses up to 0.33 s, with the observation of the *n*=1 rotating distortion associated with current relaxation processes. In the HIT and HIT–II experiments, CHI has been used to produce I_p ~ 0.25 MA, (with Te ~100 eV in HIT), and the *n*=1 rotating distortion [4,5]. This paper reports CHI startup coupled to Ohmic sustainment in HIT–II, with a savings in transformer volt-seconds and greatly improved repeatiblity with diminished wall conditions [6].

2. NSTX High Current Long Pulse Experiments

Experiments on NSTX produced high toroidal current, I_p = 0.4 MA, and pulses up to 0.33 s. A 50 kA, 1 kV DC power supply is connected across the inner and outer vessel components (the CHI electrodes) which are insulated from each other by ceramic rings at the bottom and top. A description of the CHI system on NSTX can be found in Reference [3].

2.1 NSTX Results

Figure 1 shows the toroidal current, injector current, the applied injector voltage, and the injector flux for a CHI produced discharge.

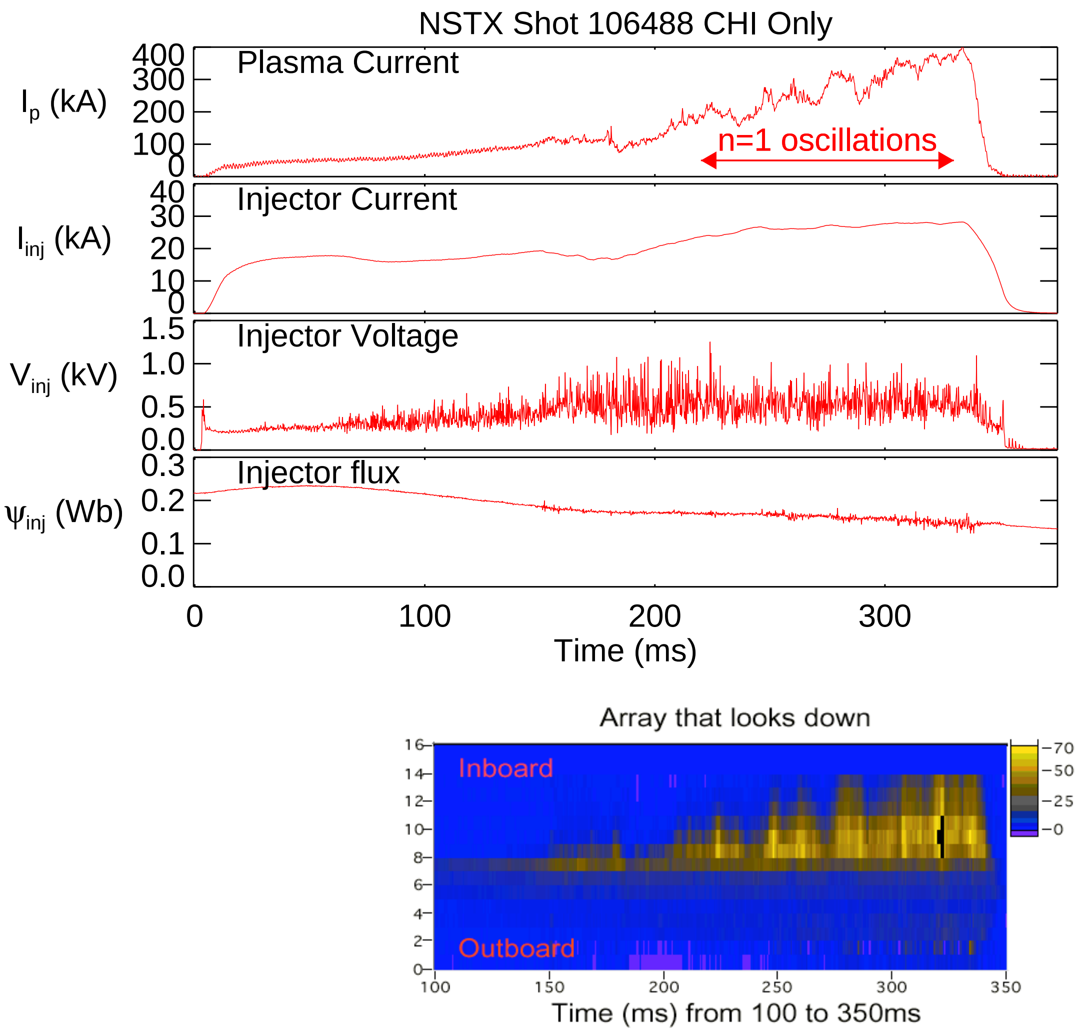

FIG. 1. CHI only drive in NSTX, upper, and soft X-ray emission, lower.

In this discharge, as the injector voltage is increased and the injector flux reduced, the toroidal current reaches nearly 400 kA. The corresponding injector current is 28 kA, resulting in a current multiplication factor of 14. The measured current multiplication is roughly equal to the ratio of the toroidal flux within the discharge region to the injector poloidal flux, which is the theoretical maximum attainable. For $t < 200$ ms, the toroidal current trace is smooth. During the subsequent high current phase, there is pronounced oscillation in the toroidal current signal and the amplitude of voltage fluctuations increases. Fast camera images of the discharge show large-scale vertical motion of the CHI plasma. A magnetic perturbation with amplitude 2 mT measured at the outboard midplane and toroidal mode number n=1 is observed, rotating toroidally in the $E_r \times B_p$ direction with a frequency in the range 5 – 12 kHz. The lower image in Figure 1 shows the soft x-ray emission for this discharge (measured by an array of detectors sensitive above approximately 100 eV) continues to increase as the toroidal current increases. The soft X-ray emission is seen mostly on the inboard side of the discharge, where the current density is higher. Measurements of the carbon line emission along a chord passing through the center of the plasma on the midplane indicate an ion temperature of about 30 eV and a toroidal rotation velocity consistent with the magnetic measurements.

2.2 NSTX Discussion

NSTX has produced the highest toroidal plasma current using CHI in an ST, and the longest pulse in any CHI experiment. A rotating toroidal distortion is seen, consistent with relaxation behaviour and observations made on all other helicity injection relaxation current drive experiments. These results show CHI engineering systems can be applied to a large ST for the production of substantial toroidal current.

3. HIT-II: CHI Startup for Ohmic Experiments

In these experiments the injector current is produced by a 4 mF, 3 kV capacitor power supply connected across the inner and outer vessel components, (insulated from each other by ceramic rings at the bottom and top). Titanium gettering and He glow discharge cleaning are used for wall conditioning to obtain the highest current discharges. HIT–II uses 24 feedback controlled power supplies to control the flux boundary conditions. This system allows application of arbitrary loop voltage waveforms.

3.1 HIT–II Results

Figure 2 shows a discharge with CHI startup and Ohmic sustainment: plasma current, injector current, injector voltage, applied loop voltage, total radiated power (from a wide angle bolometer at midplane, assuming uniform radiated power throughout the main chamber), and chord-averaged electron density (impact parameter at 0.35 m). After the CHI plasma is established at 0.5 ms, the divertor flux is ramped from 8 mWb to zero at the fastest possible rate (less than 1.5 ms). The applied loop voltage waveform is an initial 4 V flattop for $1.2 < t < 3.2$ ms and then a 3.2 V flattop for $3.2 < t < 10$ ms, resulting in a transformer half-swing of almost 30 mWb. The primary motivation for reducing the divertor flux to zero is to encourage detachment of the CHI produced plasma footprints from the divertor electrodes, and to produce a plasma containing some closed flux through forced reconnection. This reconnection is seen in discharges with the same injector flux conditions as those in Figure 2, but using only CHI, *viz.*, the plasma current persists after the injector current decays to zero.

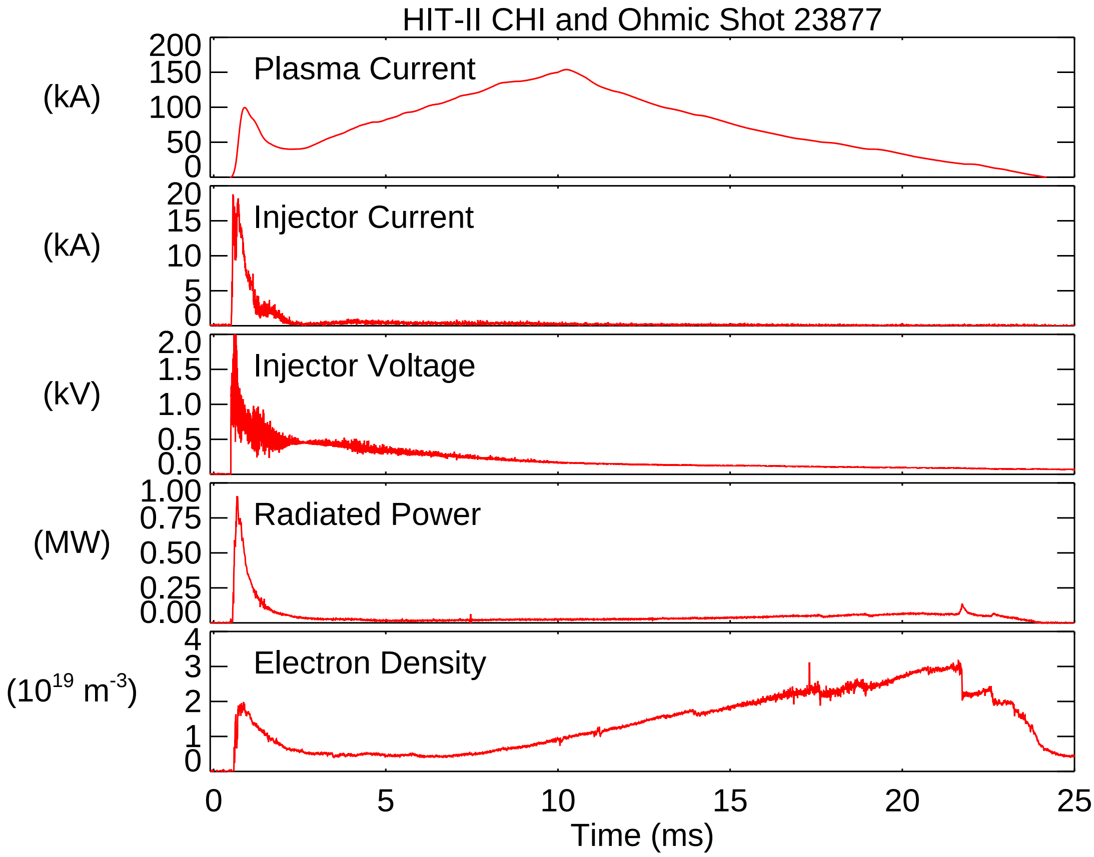

FIG. 2. CHI startup for Ohmic drive in HIT-II.

Figure 3, shows eleven traces produced in sequence starting from discharge 23915 and ending in discharge 23925. The reason for conducting this sequence of shots is to ensure that varying wall conditions are not affecting the results, and to clearly establish the differences between discharges with and without CHI startup. All discharges have the same transformer loop voltage as in Figure 2. The first nine shots are conducted in sets of three. The first shot of the set (shown in black) is a case where all the magnetic flux conditions necessary for producing the discharge in Figure 2 are used but without application of the CHI injector voltage. The second discharge in the set (shown in red) is the case where there is no divertor flux, (which is optimized for induction only plasmas for given wall conditions) and again no CHI voltage is applied. In the third discharge, number 23917, (shown in blue) a CHI capacitor voltage of 1.7 kV is used with the flux conditions of discharge 23915. This sequence is repeated two more times. For the CHI started cases, the voltage is increased to 2.1 kV and 2.4 kV respectively. As the applied CHI voltage is increased, so does the initial CHI produced plasma current and the magnitude of current that couples to the inductive drive. However, if the voltage is increased to a threshold value, 2.4 kV for this sequence of discharges (shot 23923), less of the CHI produced current couples to the inductive drive. The final two traces (magenta and cyan) also correspond to the case of discharges with CHI startup, but with the voltage reduced to 2.3 kV. These last two discharges have the highest CHI hand-off current and highest peak plasma current, even though induction-only plasmas could not be satisfactorily produced (discharges 23921 and 23922) on preceding discharges.

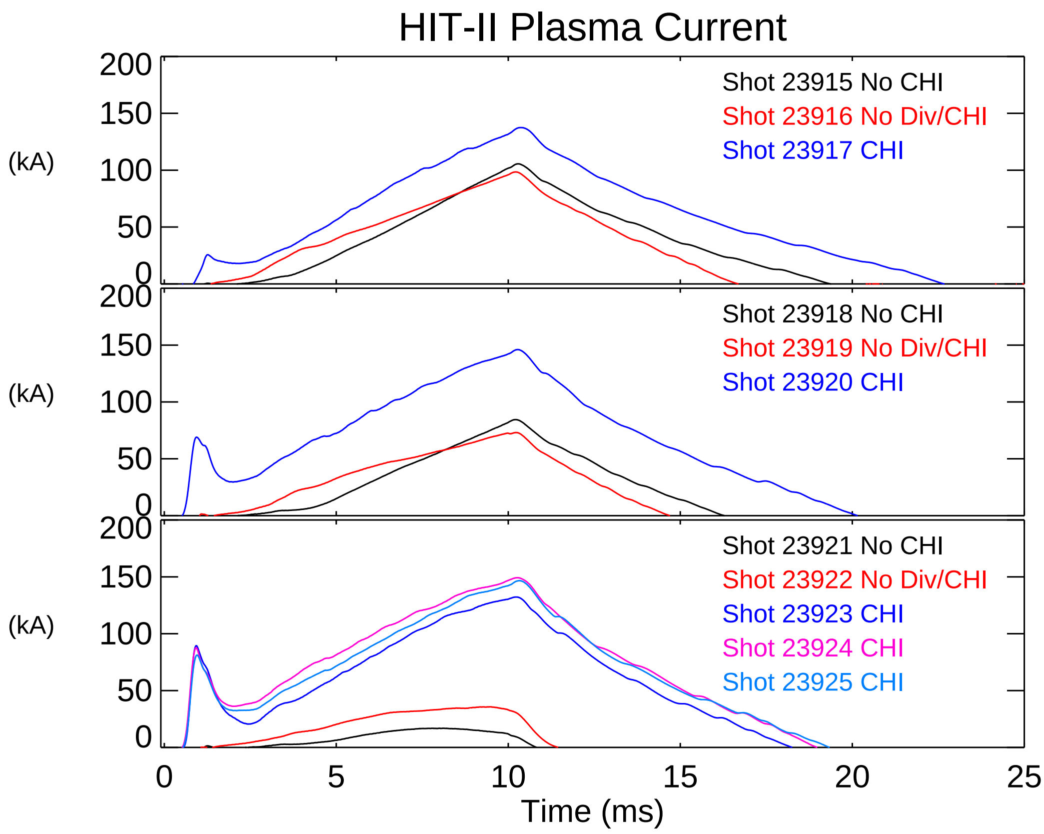

FIG. 3. Eleven sequential discharges in HIT–II.

3.2 HIT-II Discussion

Rapidly reducing the divertor flux forces reconnection in the injector region. Field line reconnection in the injector region produces a closed field line plasma configuration in the vessel, seen by the CHI-only produced plasma current lasting longer than the injector current. This existence of plasma current, when the injector current is zero, is a new result never before seen in CHI produced discharges in the HIT program nor in NSTX CHI plasmas. Since the external CHI circuit is not driving the plasma current inside the main chamber, the main chamber current can only result from the presence of closed flux.

This closed flux plasma is used as the initial target for the inductive drive provided by the central solenoid. The sequence of shots in Figure 3 clearly shows the differences between discharges produced with and without CHI startup. For the first set of shots the plasma current in discharges without CHI startup reach about 100 kA. During the second set, the currents reduce to about 80 kA and by the time of the third set the Titanium conditioning of the walls has reduced to a level where it is no longer possible to produce a high current discharge using induction alone. The cases with CHI startup remain remarkably robust even under diminished wall conditions. The threshold value of injector voltage, 2.4 kV, may be due to the increase in radiated power (seen by bolometry) indicating the generation of a more resistive CHI produced plasma in this case. Reducing the applied voltage to 2.3 kV (for the last two discharges) immediately produces the highest CHI-to-Ohmic transition currents and peak toroidal plasma currents in this sequence.

4. Summary

CHI current drive has been used on NSTX to produce record toroidal currents (0.4 MA) and pulse lengths (0.33 s). These plasmas have the characteristics of high-performance discharges seen in the HIT and HIT–II experiments, and have light emission indicating improving temperatures. Future plans include an improved upper insulator, improved noise suppression, and active feedback control of discharges.

CHI has been used to successfully startup Ohmically driven plasmas, with a resulting savings in transformer volt-seconds and greatly improving the repeatability of discharges with diminished wall conditioning. This method of startup will be implemented on NSTX.

References

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