Journal of Fusion Energy, Vol. 26, Nos. 1/2, June 2007 (© 2006)
DOI: 10.1007/s10894-006-9063-0

Solenoid-free Plasma Start-up in HIT-II and NSTX using Transient CHI

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A new method of non-inductive startup, referred to as transient coaxial helicity injection (CHI), has been successfully developed on the HIT-II experiment. In this method, a plasma current is rapidly produced by discharging a capacitor bank between coaxial electrodes in the presence of toroidal and poloidal magnetic fields. The initial poloidal field configuration is chosen such that the plasma rapidly expands into the chamber. When the injected current is rapidly decreased, magnetic reconnection occurs near the injection electrodes, with the toroidal plasma current forming closed flux surfaces. On HIT-II, CHI-started plasmas outperform discharges initiated by induction alone and consume fewer volt-seconds. The method has now been successfully applied on NSTX for an unambiguous proof-of-principle demonstration of closed-flux current generation without the use of the central solenoid.

KEY WORDS: CHI; ST; non-inductive current drive.

INTRODUCTION

The Spherical Torus (ST) is a low-aspect-ratio tokamak [1]. As a result of the low aspect ratio, the projected bootstrap current drive in these devices may exceed 80% reducing the requirements for maintaining the plasma current in steady state. However, the low aspect ratio, as well as the need for neutron shielding in a future reactor, also reduce the space available for a central solenoid, limiting its capability to generate the initial current and to supplement the bootstrap current in steady-state. The ST and some tokamak designs (for example the ARIES-AT and RS [2], which are designed without a central solenoid) can be considerably simplified by entirely removing the central solenoid, because in a steady-state device the technologically challenging central solenoid is needed mainly for the current start-up phase of the discharge. Viability of the ST concept requires a demonstration of plasma startup without the use of the central solenoid.

Coaxial Helicity Injection (CHI), a method originally developed for spheromak formation, is a promising candidate for initial plasma startup. It also has the potential for providing edge current drive during the non-inductive sustained operation phase. On HIT-II [3] and on NSTX [4], CHI is implemented by driving current along externally produced field lines that connect coaxial electrodes mounted on the electrically isolated inner and outer vacuum vessel components in the presence of externally generated toroidal and poloidal magnetic fields. In NSTX, the inner and outer annular target plates of the poloidal divertor at the bottom of the vacuum vessel serve as the electrodes. A major difference between these experiments is that the NSTX vessel volume is 30 times larger than HIT-II.

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CHI DISCHARGE INITIATION

A CHI discharge is initiated by first producing poloidal field connecting the injector electrodes with poloidal field coils outside the vessel structure. This poloidal field in combination with the toroidal field produces a helical field line structure in the injector region. Application of sufficient voltage to these electrodes in the presence of fuel gas causes the gas to breakdown. The resulting current flows on field lines connecting the electrodes.

Increasing the applied voltage increases the injector current. At sufficiently high injector currents, the resulting $\Delta \mathbf{B}^2_{\mathrm{tor}}$, $\mathbf{J}_{\mathrm{pol}} \times \mathbf{B}_{\mathrm{tor}}$, stress across the current layer exceeds the field line tension of the injector flux, causing the helical current structure to move into the main plasma chamber. Rogowski coil sensors around the device measure the toroidal plasma current. This toroidal current is approximately the injected current times the ratio of the enclosed toroidal flux to the amount of injector flux that has extended into the vessel [5]. This process, referred to as *driven* CHI or *steady-state* CHI, can, in principle, be sustained indefinitely. Using this method, CHI discharges lasting up to 0.4 s have been produced on the NSTX device. It is important to note that the toroidal current produced by CHI initially flows on open field lines. Relaxation activity or other processes, such as forced axi-symmetric reconnection, are needed to transfer some of this current onto closed field line regions. The creation of closed field line current in a driven CHI system, which is eventually needed for sustainment of non-inductive discharges, is a subject of ongoing research. However, the experiments described here and referred to as *transient* CHI, use pulses of CHI much shorter than the current relaxation timescale solely for the purpose of plasma current startup.

TRANSIENT CHI RESULTS

For transient CHI, the source current, referred to as the injector current, is provided by a small capacitor bank (4 mF, 3–4 kV on HIT-II and 15 mF, 1.5 kV on NSTX) that is connected across the outer and inner vessel components at one axial end of the machine referred to as the injector region [4]. The opposite end is referred to as the absorber, as the $\mathbf{E} \times \mathbf{B}$ drift is into this region. Electrical separation of the inner and outer vessel components is achieved by toroidal ceramic insulators at both ends of the machine. The capacitor power supply is switched by an ignitron and the circuit is over-damped by a series resistor.

That transient CHI works very well is demonstrated by representative discharges in the HIT-II device, which are shown in Figures 1 and 2. In Figure 1, discharge 27518 is produced inductively using pre-programmed inductive voltage from the central solenoid. On the subsequent discharge 27519, under identical conditions the same loop

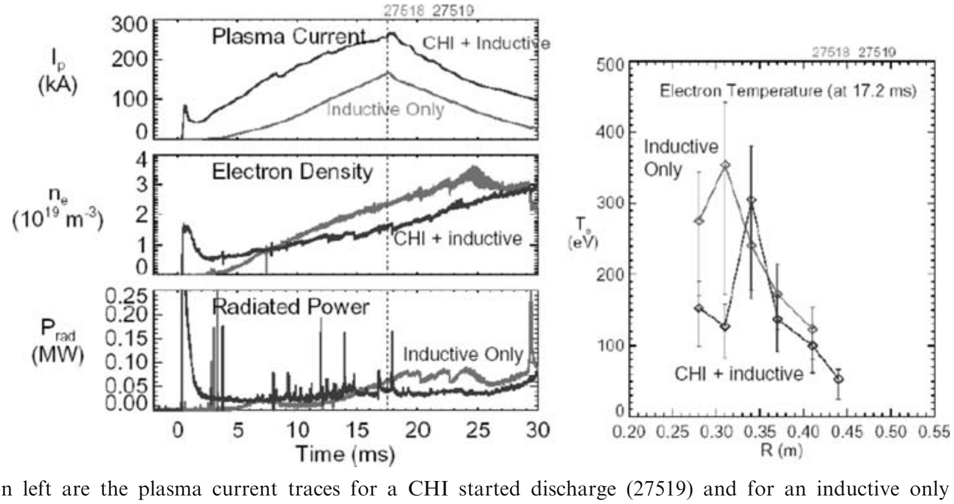

Fig. 1. Shown on left are the plasma current traces for a CHI started discharge (27519) and for an inductive only discharge (27518) with the same loop voltage programming and gas injection conditions. The line averaged electron density, the radiated power and the local electron temperature from a Thomson scattering diagnostic are also shown. The data shows that the HIT-II device generates inductive plasmas and CHI started inductive plasmas with parameters typical of those produced by tokamaks with similar levels of plasma current.

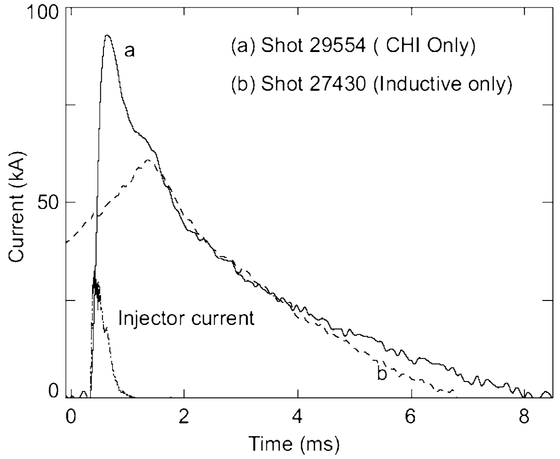

Fig. 2. The plasma current decay rate from a CHI only discharge and from an inductively started discharge at similar levels of closed flux current (~60 kA) are compared. Such a direct comparison of CHI produced discharges to inductive discharges was first conducted on the HIT-II experiment and clearly shows that CHI, which uses electrode discharge for plasma formation, is capable of producing high quality plasma. Note that after the injector current has been reduced to zero, the persisting CHI produced plasma current must contain closed flux equilibrium.

voltage programming is applied to a discharge initiated using CHI. The initial spike in the plasma current, which reaches 75 kA, is entirely produced by CHI. As the initial plasma current decays, induction is applied from the central solenoid. The dramatic increase in the plasma current demonstrates that discharges produced using the CHI startup process not only couple to the conventional inductive method, but outperform inductive-only operation by nearly doubling the current attained by induction alone. In this discharge the central solenoid was pre-charged to -22 mWb and then ramped up to $+30$ mWb for a total 52 mWb flux swing in the central transformer. The radiated power trace shows it to be high during the initial CHI formation phase, however, as density is pumped out of the CHI produced equilibrium the radiated power rapidly reduces in magnitude. At the time of inductive voltage application it is below the inductive input power of about 100 kW. In Figure 2, the current decay time scales from a CHI only discharge are compared to an inductively produced discharge. The 8 ms current-decay time for these plasmas is consistent with the measured electron temperatures of 20–30 eV. Recently, NSTX has demonstrated the observation of toroidal current persistence after the injector current was reduced to zero [6].

CONTRASTING NSTX WITH HIT-II

An important difference between the NSTX and HIT-II results with transient CHI are that the injector current on NSTX was typically about 2 kA, whereas on HIT-II it is typically 15–30 kA. The current multiplication ratio of the plasma current to injector current on HIT-II is 6–7, whereas NSTX has achieved a current multiplication ratio up to 70. This favorable scaling of CHI with increasing the machine size, summarized in Table 1, occurs because the current multiplication factor, which is obtained from the condition for helicity injection threshold, given as $I_p = I_{inj}(\psi_{Toroidal}/\psi_{inj})$ increases in proportion to the toroidal flux [5]. However, Table 1 also shows the theoretical maximum for the current multiplication to be about twice that achieved by both machines.

In a given device, as the toroidal flux is increased at fixed injector flux, the length of the field lines linking the electrodes increases, which would be expected to increase the impedance of the injector circuit. This is seen in both HIT-II and NSTX. The increase in impedance is compensated by increasing the power supply voltage. On NSTX, the field line length between the electrodes is about ten larger than on HIT-II. Although it might therefore be expected that the required voltage would also be higher, the observation is the opposite: NSTX is able to inject the same amount of flux at much lower capacitor bank voltage. This important, and favorable, observation is believed to result from the higher conductivity of the CHI produced plasma in NSTX. It is well established that in hot tokamak discharges MA-level currents can be sustained by voltages less than 1 V per toroidal turn, corresponding to an injector

Table 1. Representative parameters for HIT-II, NSTX and NSST

Parameter	HIT-II	NSTX	NSST
R (m)	0.3	0.86	1.5
a (m)	0.2	0.68	0.9
Vol (m^3)	0.36	11.2	38
B_T (T)	0.43	0.41	2.6
k (elongation)	1.5	2.3	2.7
ψ_T (Wb)	0.13	1.30	16
ψ_{inj} (mWb)	8	10	10–50
I_p/I_{inj} (Meas)	6	70	NA
I_p/I_{inj} (Calc)	16	130	1600–320
I_{inj} (kA)	15–30	2	2–30
I_p (MA)	0.1	> 0.15	> 1
L_p (μH)	~0.5	~0.5	< 0.5
$E_{indctive}$ (kJ)	2.5	> 6	~250

voltage of about 70 V for the maximum achieved multiplication ratios.

The implications of these scaling results are quite favorable for a larger ST, such as NSST [7] which has a major radius $R = 1.5$ m, maximum toroidal field on axis $B_{\mathrm{T}} = 2.6$ T and a toroidal flux $\psi_T = 16$ Wb. For similar values of the injector flux and injector voltage as on NSTX, CHI produced toroidal plasma currents in excess of 1 MA are not unrealistic in NSST. At this level of current, other well-established non-inductive current drive methods, such as neutral beam injection, could ramp the current to the full levels of 5–10 MA needed in NSST. These discharges would require modest levels of capacitor bank energy of about a few times the inductive stored energy in the CHI produced discharge.

CONCLUSION

In conclusion, the method of transient CHI has been show to work very well in HIT-II, consistently out performing inductive-only current ramp-up. It has been shown to produce significant levels of useful seed closed-flux plasma current for the purpose of solenoid-free plasma startup. The method has now been demonstrated on NSTX, although further optimization is required to realize the full potential of this method on NSTX. Extrapolation to large machines appears very favorable.

We acknowledge the NSTX and HIT-II teams for support with machine operation and diagnostics. This work is supported by DOE Contract numbers: FG03-96ER5436, DE-FG03-99ER54519 and DE-AC02-76CH03073.

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