Demonstration of 300 kA CHI Startup Current Coupling to Transformer Drive on NSTX

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Abstract. Discharges started by Transient Coaxial Helicity Injection (CHI) in NSTX have attained peak currents up to 300 kA for the first time. When these discharges are coupled to induction, it has produced over 200 kA additional current over inductive-only operation. For the first time, the CHI-produced toroidal current that couples to induction has continued to increase with the energy supplied by the CHI power supply at otherwise similar values of the injector flux. Furthermore, CHI in NSTX has shown to be energetically quite efficient, producing a plasma current of about 10 A/Joule of capacitor bank energy. These results indicate the potential for substantial current generation capability by CHI in NSTX and in future toroidal devices.

1. Introduction

The spherical torus [1] (ST) is a low aspect-ratio toroidal magnetic confinement concept featuring the advantages of high beta and a high fraction of bootstrap current. Because of the low aspect ratio, elimination of the central solenoid is very important for the next generation of ST experiments and is essential for the viability of the ST concept as a reactor. Non-inductive methods for plasma current startup and sustainment therefore become necessary. An alternate method for plasma startup could also reduce the cost of a future tokamak reactor as indicated by the ARIES design studies [2]. The National Spherical Torus Experiment (NSTX) is exploring the technique known as Coaxial Helicity Injection (CHI) [3] as a method to produce the initial plasma and sufficient toroidal plasma current to allow other methods of non-inductive current generation and sustainment to be applied.

CHI is a promising candidate both for plasma startup and for edge current drive during the sustained phase. The possibility of using CHI in an ST was first proposed in the late 1980's [3]. Helicity injection current drive in a ST was first conducted on the Current Drive Experiment-Upgrade (CDX-U) at the Princeton Plasma Physics Laboratory (PPPL) [4]. As a result of experiments conducted on the Proto-Helicity Injected Torus, and the Helicity Injected Torus-I (HIT-I) at the University of Washington [5] the concept gained support. These HIT experiments used a thick conducting copper wall for equilibrium control of the CHI produced plasma configuration. Two other experiments that used CHI are the Helicity Injected Spherical Torus (HIST) in Japan and the SPHEX device in the UK. [6,7] These devices also employed passive wall stabilization for equilibrium control and confirmed that CHI could be used in the presence of an external toroidal field for the generation of a plasma configuration. Later HIT was rebuilt as the HIT-II experiment, which extended CHI to a true ST device by employing poloidal field coils for equilibrium control and transformer action. Later the method was adapted to the NSTX device, which employs standard tokamak components. [8]

It is generally accepted [9] that the development of non-axisymmetric plasma perturbations is needed for plasma startup during which the CHI injector circuit is continuously driven under near steady-state conditions for some time ($t_{pulse} > t_{L/R}$). This mode of CHI, also referred to as *steady-state* or *driven* CHI was the method initially tried on NSTX and used in other devices [10,11]. A significant recent development has been the demonstration of a new mode of CHI operation on an ST, referred to as *transient CHI* [12] analogous to fast formation ($t_{pulse} << t_{L/R}$) on spheromaks [13,14]. Transient CHI appears to involve an axisymmetric reconnection (or nearly-axisymmetric reconnection) and was highly successful on the HIT-II experiment. While the steady-state approach is still needed for sustained edge current drive, transient CHI has been extremely successful on HIT-II for the purpose of plasma startup. Recent results from the successful application of the transient CHI method in NSTX are described in the subsequent sections.

2. Implementation of CHI on NSTX

Implementation of CHI on NSTX draws on extensive experience from the HIT and HIT-II experiments at the University of Washington, and work elsewhere [15,16,17,18,19,20]. The NSTX device is described in Ref. [21]. To accommodate CHI, the NSTX stainless steel vacuum vessel (nominal major radius 0.85 m, volume 30 m^3) has separate inner and outer sections, electrically isolated from each other by toroidal ceramic rings at the top and bottom which also act as vacuum seals. The inner divertor plate (part of the center stack assembly) is thus electrically separated from the outer divertor plate, which is attached to the outer vessel, as illustrated in FIG. 1. The poloidal field coils located beneath the lower insulated gap are used to produce poloidal flux connecting the lower inner and outer divertor plates, as indicated qualitatively by the circle in FIG. 1(b). A small amount of deuterium gas is introduced into the chamber and a voltage (typically 1 kV – 2 kV) is applied between the plates, forming a discharge with current flowing in the plasma from the outer divertor plate to the inner lower divertor plate, as shown by an arrow in FIG. 1(b). In the presence of a toroidal field, the plasma current, which essentially flows along field lines, develops a toroidal component. The bright region at the top of FIG. 1(c) is the top of the CHI plasma that has extended to approximately the middle of the vessel at a time during the discharge when the plasma current is below the peak value. As the plasma current increases to near the peak value, the discharge further elongates to fill the vessel as shown in FIG. 1(d). The bright ring shaped region at the top of this image is referred to as an absorber arc, a condition when part of the injector current bridges the upper divertor gap. We refer to the lower gap connected by the poloidal field as the injector and the complementary upper gap as the absorber because when voltage is applied toroidal flux flows out of the injector and into the absorber.

The toroidal plasma current produced by CHI initially flows on open field lines joining the electrodes. To produce toroidal plasma current on closed flux surfaces, magnetic reconnection or some dynamo activity occurs. In steady state, this current drive depends on non-axisymmetric plasma perturbations. In transient CHI, the initial poloidal field magnitude is chosen such that the plasma carrying the injected current rapidly expands into the chamber. When the injected current is rapidly decreased, axisymmetric magnetic reconnection occurs near the injection electrodes, with the toroidal plasma current forming closed flux surfaces. The method of transient CHI has now been successfully used on NSTX for an unambiguous demonstration of closed-flux current generation without the use of the central solenoid. The CHI capacitor bank has several requirements on current, voltage, energy, and current multiplication, which are discussed in detail in Refs. [22,23].

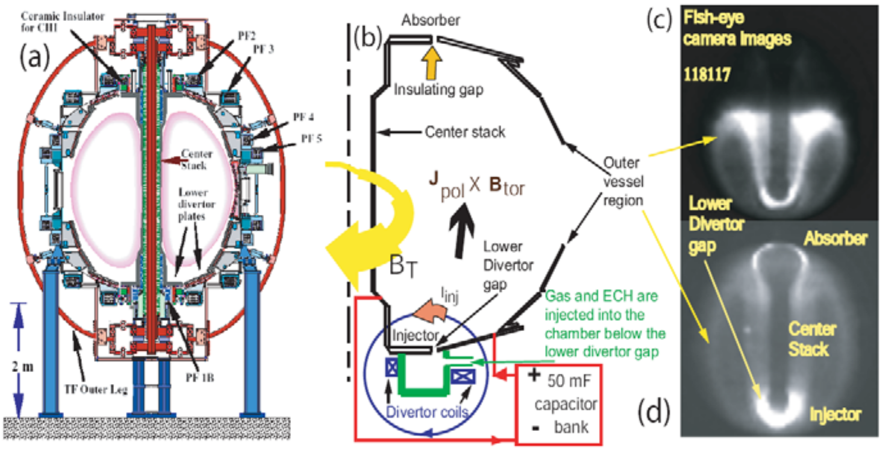

FIG. 1(a) NSTX machine layout showing the location of the toroidal insulator and external poloidal field coils. (b) Components used for CHI startup in NSTX and (c) fast camera fish eye images showing discharge evolution from near the injector region and (d) later during the discharge.

2.1 Previous Transient CHI Startup Results on HIT-II and NSTX

The method of 'Transient CHI startup' in a ST was developed on the HIT-II ST at the University of Washington [12]. A feature of CHI plasma generation using this method is that unambiguous flux closure can be demonstrated by the persistence of plasma current after the injector current has been reduced to zero. Closed flux is achieved by proper programming of the injector voltage, which can be easily achieved using a small capacitor based power system. The method does not rely on time-changing poloidal field coil currents making it very attractive for reactors in which poloidal field coils would be located outside conductive vessel components and blanket structures. It saves Volt-seconds and is much less sensitive to field errors and changing wall conditions than inductive startup alone [24].

On HIT-II, which used graphite for the center stack and tungsten-coated stainless steel for the outer vessel, even with 30 kA of injected current the radiated power could be kept lower than the input Ohmic power. Because of this, HIT-II discharges initiated by CHI showed significant saving of the inductive flux required to reach a given plasma current. A corresponding savings of inductive flux was not demonstrated in NSTX during the FY2008 campaign.

2.2 FY2009 Transient CHI Startup Results on NSTX

Recent studies have shown transient CHI startup: demonstrates transformer flux savings [25]; performs better with proper electrode conditioning to reduce impurities [22] as well as careful programming of the absorber coils [23]; and can produce H-mode plasmas with neutral beam injection [22]. More recent results presented here expand upon these studies.

To reduce the level of low-Z impurities in the CHI started discharges so that discharges produced with more than two capacitors could be coupled to induction two impurity control techniques were used in FY2009 and found to be critical for the clear demonstration that CHI startup is equivalent to and compatible with Ohmic start-up.

First, the lower divertor electrodes were cleaned by running about thirty 400 ms long CHI discharges with a large value of poloidal flux connecting the lower divertor plates (the injector flux) and limiting the magnitude of the injector current to about 5 kA so that the resulting discharge stayed connected to the lower divertor plates. This electrode conditioning process reduced the level of low-Z impurities, particularly oxygen, measured spectroscopically during the CHI startup. Second, two poloidal field coils located in the upper divertor region were energized for the first time to provide a “buffer” flux to reduce contact of the growing CHI discharge with the upper divertor electrodes. In the absence of this buffer flux, once the CHI discharge contacted the upper (absorber) divertor electrodes, an absorber arc usually developed which generated undesirable impurities and reduced the amount of current in the injector.

The improvement in performance of CHI-started discharges as the size of the capacitor bank is increased is shown in FIG. 2. Each discharge benefited from the use of 100 mg of lithium evaporation beforehand. With a single capacitor (5 mF), about 120 kA of plasma current is produced. At the higher levels of capacitor bank energy, not only does the initial current increase, but the current during induction is higher than with induction alone. This improvement is also reflected in the electron temperature which reached 50 eV for the first time during the CHI phase. The temperature remains high with increasing CHI power supply energy whereas it previously fell as the impurity level increased. This is the first such observation in NSTX that indicates that low-Z impurity levels in these plasmas are now at a sufficiently low level so that additional capacitor bank energy contributes to plasma heating rather than being lost through impurity line radiation. At the temperatures achieved, the oxygen radiation barrier is exceeded, thereby allowing the rapid ramp up in the current when the induction is applied. These results indicate that the methods used for low-Z impurity control in NSTX have been effective. Further improvements are still possible, which should increase the CHI current start-up potential in NSTX.

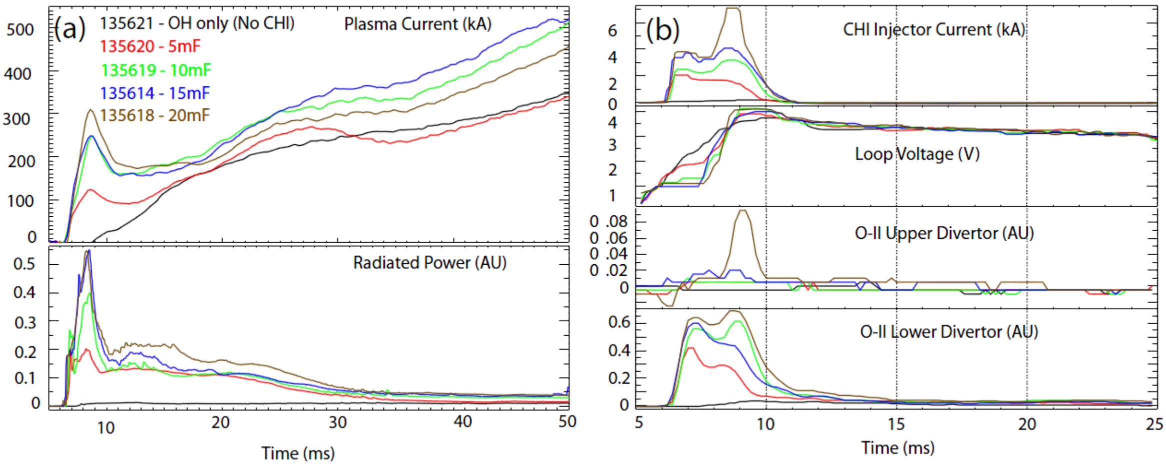

FIG. 2: (a) Shown are plasma current and radiated power traces from a scan in the size of the CHI capacitor bank power supply from 5 to 20 mF (all charged to 1.7 kV). Discharge 135621 is a reference inductive-only discharge. (b) CHI injector current and spectroscopic traces for the four discharges.

For the discharge shown in FIG. 2 using 15 mF (three capacitors), at 48 ms, nearly 200 kA of additional current is present and retained over the reference inductive-only discharge. All discharges had identical programming of the central solenoid loop voltage. At 50 ms, 0.11 Wb of central solenoid flux has been applied. When applied to the CHI started discharge (135614), the current reached 525 kA, whereas in the inductive-only discharge (135621), the current reached only 325 kA [25]. Both the electron temperature and density profiles for the CHI-initiated discharge (135614) were higher than for the reference inductive-only discharge so that the plasma pressure was nearly doubled [25]. Discharge 135618 with four capacitors reached an initial peak of 300 kA, which is a record for transient CHI-started discharges in a ST or tokamak. The initial stored capacitor bank energy is 27 kJ, which is quite modest.

Although this too subsequently shows better performance than the inductive-only discharge, it is not as good as that for the two and three capacitor cases. The reason for this is seen in FIG. 2(b) which shows that the constant value of buffer field that was used for all cases was inadequate for this higher current discharge as an absorber arc occurred and consequently there was additional impurity influx. Because of this arc, not all of the 27 kJ is used to produce the CHI discharge, so that the energy efficiency is much better than 10 A/J. Clearly more buffer flux is required for the higher current CHI discharges but in these experiments, the absorber PF coil currents were limited by their power supplies. In FIG. 2(b) for discharge 135618, the injector current shows the pronounced current spike related to absorber arcing, there is a simultaneous increase in the upper divertor O-II signal, and the radiated power stays elevated.

For all cases shown in FIG. 2, the current multiplication at the time of the peak current during CHI is approximately that given theoretically by the flux multiplication ratio: $I_p = I_{inj}(\phi_{plasma} / \psi_{injector})$. Here ϕ_{plasma} is the total toroidal flux inside the plasma and $\psi_{injector}$ is the injector poloidal flux measured as the poloidal flux that connects the lower inner CHI electrode to the outer electrode. For all these discharges at the time of CHI discharge initiation there is 20 mWb of injector flux connecting the lower divertor electrodes. At the toroidal field of 0.52 T used in these discharges, the maximum toroidal flux in the NSTX vessel is 2.0 Wb, so the theoretical maximum current multiplication is ~100. For the discharges in FIG. 2 the current multiplication ranges from 70 to 100. What is important about these results is that, even though the injector flux for all cases remains the same and all discharges have about the same value of current multiplication, the CHI-produced toroidal current continues to increase with increasing capacitor bank energy. The maximum achievable toroidal current in these discharges is limited by the influx of low-Z impurities that does increase with injector current. If the injector current could be doubled (for example, by doubling the number of capacitors), while maintaining a low influx of impurities, then, in principle an initial start-up current of about 600 kA should be realizable in NSTX. It should be noted that the small HIT-II device, built solely to study CHI physics, was able to routinely run at 30 kA of injector current without encountering any impurity issues [26]. This suggests that the present injector current limits of about 4 kA on NSTX have considerable room for improvement. Moreover, the higher electron temperature trend of increasing CHI initiated plasma current implies that it should be feasible to directly couple the high harmonic fast wave heating [27] to further ramp-up the plasma current non-inductively.

3. Recent Transient CHI Startup and Coupling Results on NSTX

The most recent experiments in which CHI initiation was followed by inductive ramp-up produced final currents exceeding 1 MA using only 0.28 Wb of the 0.33 Wb of the inductive flux available from a uni-directional swing of the central solenoid. This is the highest current produced in NSTX using this amount of central solenoid flux without auxiliary heating, and is a significant improvement over the 800 kA achieved using all of the flux from a single swing of the central solenoid in 2009 and described in [25]. The improvements were obtained by more effective use of the absorber coils to reduce absorber arcs, and reducing impurities originating from the CHI electrodes by increased use of lithium coatings. Coupling of CHI-started currents to induction and ramping up to high current this campaign was possible using up to 5 capacitors. FIG. 2 is a comparison of two discharges, one with CHI start-up coupled to induction and the second with induction only.

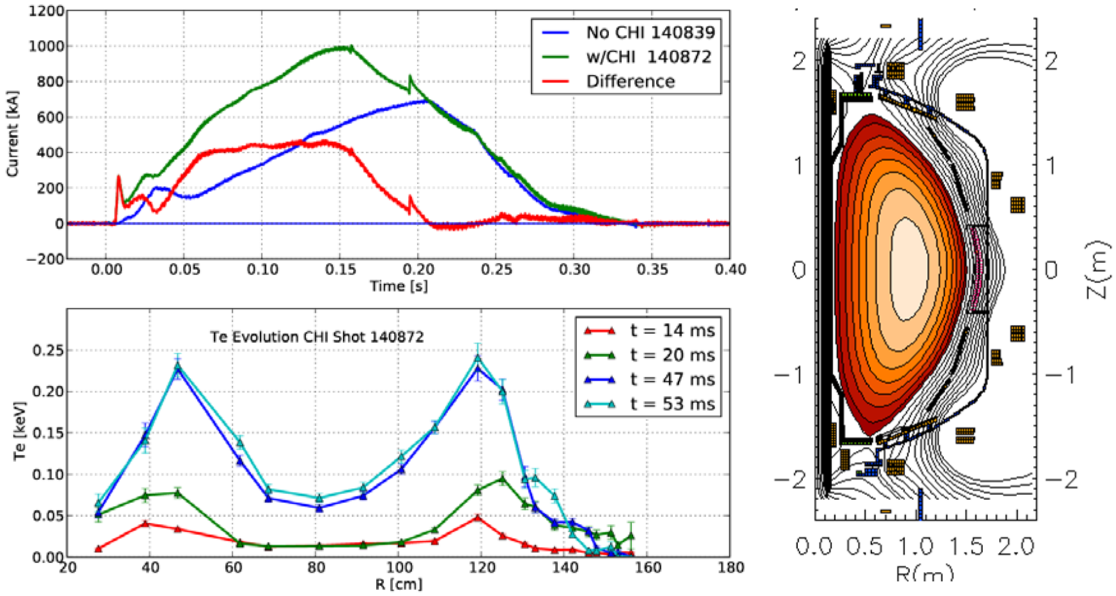

FIG. 3. (Top left) The green trace is a discharge started with CHI (at 6 ms) and coupled to induction reaching 1MA at 150 ms. The comparison discharge(blue trace) using the same loop voltage programming, without CHI start-up gets to 600 kA at the same time. The red trace shows the current difference between the two discharges. (Bottom left) Electron temperature profiles at various times. (Right) EFIT reconstruction of discharge 140872 at 100 ms (courtesy: S. Sabbagh).

The electron temperature during the transition phase from CHI to induction (around 20 ms) reached 100 eV in many shots. The shots with such high early electron temperatures ramped-up to the highest currents. In previous discharges, the electron temperature did not reach 100 eV until around 50 ms. Now at 50 ms, a peak temperature of nearly 250 eV is reached off-axis with the core electron temperature approaching 100 eV. The hollow electron temperature profile characteristic of CHI start-up, is now retained during most of the current ramp. FIG. 3 shows an equilibrium reconstruction at 100 ms which includes Thomson scattering electron temperature and density profiles and the measured diamagnetic flux as constraints on the pressure profile. These plasmas have both a very high elongation of $\kappa \approx 2.6$ and, as a result of the hollow electron temperature profile and rapid inductive ramp, very low internal inductance $l_i \approx 0.3$ from the start of the discharge. Finally, these plasmas are relatively free of MHD activity despite having low density, which has previously been associated with increased instability during normal inductive startup. Tokmak Simulation Code runs indicate that these targets should be capable of reaching a high fraction of neutral beam driven current. Thus, the 2010 campaign has not only significantly improved CHI startup capability, but also produced the type of plasmas that are needed to meet the objectives of the non-inductive start-up and ramp-up program of NSTX.

4. Summary and Future Plans

Transient CHI in NSTX produces nearly 300 kA of start-up current and is coupled to induction. The significance of these results are (a) demonstration of the process in a vessel volume thirty times larger than HIT-II, on a size scale more comparable to a reactor, (b) a remarkable multiplication factor up to 100 between the injected current and the achieved toroidal current, compared to 6 in HIT-II experiments, showing favourable scaling with machine size, (c) coupling and savings of inductive flux in a machine built with carbon walls, (d) very high current generation efficiency of 10 A/Joule of initial stored energy and the capability to generate high levels of plasma current.

The most recent NSTX experiments in which CHI initiation was followed by inductive ramp-up produced currents exceeding 1 MA using only 0.28 Wb of the 0.33 Wb of the inductive flux available from a uni-directional swing of the central solenoid. This is the highest current produced in NSTX using this amount of central solenoid flux, and is a significant improvement over the 800 kA achieved using all of the flux from a single swing of the central solenoid in 2009. These plasmas have both a very high elongation of $\kappa \approx 2.6$ and, as a result of the hollow electron temperature profile and rapid inductive ramp, very low internal inductance $l_i \approx 0.3$ from the start of the discharge. Finally, these plasmas are relatively free of MHD activity despite having low density, which has previously been associated with increased instability during normal inductive startup. TSC simulations indicate that these targets should be capable of reaching a high fraction of neutral beam driven current. Thus the 2010 campaign has not only significantly improved CHI startup capability, but also produced the type of plasmas that are needed to meet the objectives of the non-inductive startup and ramp-up program of NSTX.

Future plans include increasing the number of capacitors in the CHI bank to achieve higher transition currents, coupling to non-inductive current drive techniques, such as high-harmonic fast wave, and exploration of the high- κ, low- l_i plasmas produced by transient CHI.

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