Plasma Start-up In NSTX Using Transient CHI

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ABSTRACT

The method of plasma generation known as Coaxial Helicity Injection (CHI) has been successfully applied in the National Spherical Torus Experiment (NSTX) to form closed, nested magnetic surfaces carrying a plasma current up to 160 kA. In some discharges the generated current persists for a surprisingly long ~400 ms. While the CHI method has previously been studied in smaller experiments, such as the Helicity Injected Tokamak (HIT-II) at the University of Washington, 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 of 60 between the injected current and the achieved toroidal current, compared to six in previous experiments, and (c) for the first time, fast time-scale visible imaging of the entire process that shows discharge formation, disconnection from the injector and the reconnection of magnetic field lines leading to closed flux. These significant results indicate favorable scaling with machine size.

1. INTRODUCTION

The spherical torus [1] is a low aspect-ratio toroidal magnetic confinement concept that has 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. The National Spherical Torus Experiment (NSTX) is exploring the technique known as Coaxial Helicity Injection (CHI) [2] 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.

The NSTX device is described in Ref. [3]. In order to accommodate CHI, the 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, which is part of the center stack assembly, is then electrically separated from the outer divertor plate, which is attached to the outer vessel. This is illustrated in Fig. 1. For CHI, the poloidal field coils located beneath the lower insulated gap are used to produce poloidal flux linking the lower inner and outer divertor plates, as indicated qualitatively by the circle in Fig. 1b. When a small amount of deuterium gas is introduced into the chamber and a voltage (typically 1 – 2 kV) is applied between the plates, a discharge forms with current flowing in the plasma from the outer divertor plate to the inner lower divertor plate, as shown by the arrow in Fig. 1b. 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. 1c 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 vertically to fill the vessel as shown in Fig. 1d. 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. In order to produce toroidal plasma current on closed flux surfaces magnetic reconnection must occur. In steady state, this reconnection depends on the development of some form of non-axisymmetric plasma perturbation. This mode of CHI operation, in which the injector circuit is continuously driven for a time longer than the timescale for resistive decay of the toroidal current ($t_{pulse} > \tau_{L/R}$), was studied in the early CHI experiments in NSTX [4]. A significant development during the past three years has been the demonstration of a new mode of CHI operation, referred to as *transient* CHI [5] and involving only axisymmetric magnetic reconnection. This method was originally developed on the HIT-II experiment [5]. In transient CHI, the initial poloidal field configuration is chosen such that the plasma carrying the injected current 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. The method of transient CHI has now been successfully used on NSTX producing an unambiguous demonstration of closed-flux current generation without the use of the central solenoid.

2. TRANSIENT CHI STARTUP

The first attempts to apply transient CHI in NSTX used the same programmable rectifier power supply that had been used for the earlier steady-state CHI experiments [4]. For transient CHI, it is advantageous to reduce the amount of gas injected for initiating the discharge in order to maximize the temperature of the resulting plasma. However, when the gas pressure was reduced, the time to breakdown increased and the thyristor switches were incapable of maintaining the voltage across the open circuit. A capacitor based power system was therefore installed, designed to satisfy several requirements for the transient CHI experiments in NSTX.

The first requirement is that there must be sufficient energy in the capacitor bank to produce the “bubble-burst” current, i.e. the injector current I_{inj} at which the $J_{pol} \times B_T$ force can overcome the field line tension in the injector, and cause the plasma to expand into the chamber above. The minimum injector current to meet the bubble burst condition is given as $I_{inj} = 2\psi_{inj}^2/(\mu_o^2 d^2 I_{TF})$, where I_{TF} is the current in the toroidal field coil and d is the width of injector flux “footprint” [6] on the electrodes. On NSTX, the lower divertor coils located outside the vessel are used to control the width of the flux footprints. The dependence of the required injector current on the square of the injector flux and the inverse dependence on the current in the toroidal field coil has been confirmed in the HIT-II experiments and in previous NSTX experiments. For NSTX, injector currents from a few to about 30 kA are needed.

The second requirement is related to how quickly the CHI discharge can fill the vessel. This is dependent on the applied injector voltage as this sets the rate at which toroidal flux crosses the injector and absorber gaps: $V_{inj} = d\phi_{tor}/dt$. For nominal NSTX conditions with 0.3 T on axis, there is about 1.4 Wb of toroidal flux inside the vessel. For 1 kV across the injector electrodes, the time needed to displace all of the toroidal flux within the vacuum vessel is about 1.4 ms. The pulse duration of the capacitor bank in NSTX satisfies this requirement.

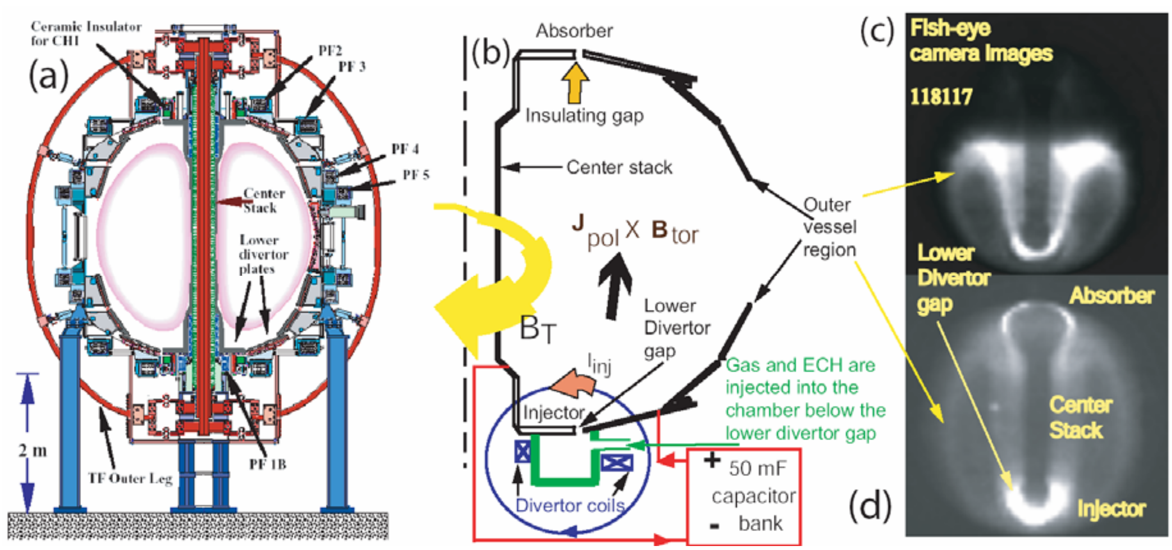

Figure 1: (a) The NSTX machine layout showing the location of the toroidal insulator and external poloidal field coils. Shown also are (b) the NSTX machine components used for CHI startup in NSTX and fast camera fish eye images showing (c) discharge evolution from near the injector region and (d) later during the discharge. Both gas and 18 GHz microwave power are injected in to a 100 Liter toroidal cavity beneath the lower divertor plates. The gas, which is ionized by the microwaves, emerges from the gap between the lower divertor plates, which eases the requirements for breakdown when the main capacitor bank discharge is initiated.

The third requirement is that there should be sufficient electrical energy in the capacitor bank to fully ionize and heat all of the injected gas. Typically about 50 eV per ion is needed for ionization and about an additional 60 eV per ion to increase the plasma temperature to 20 eV. In previous experiments, the lowest amount of injected gas that could be injected and still achieve reliable breakdown was too high to achieve a reasonable temperature. To overcome this limitation, the gas injection for CHI was changed from four ports in the lower inner divertor plate to a single port in the small (~100 l) cavity below the toroidal gap between the plates. In addition 10 kW of 18 GHz microwave power was injected into the cavity to pre-ionize the gas. These changes allowed breakdown to be achieved with much less total gas injected. The energy needed for ionizing and heating the injected gas was thereby reduced to a few kJ, less than that available in the bank.

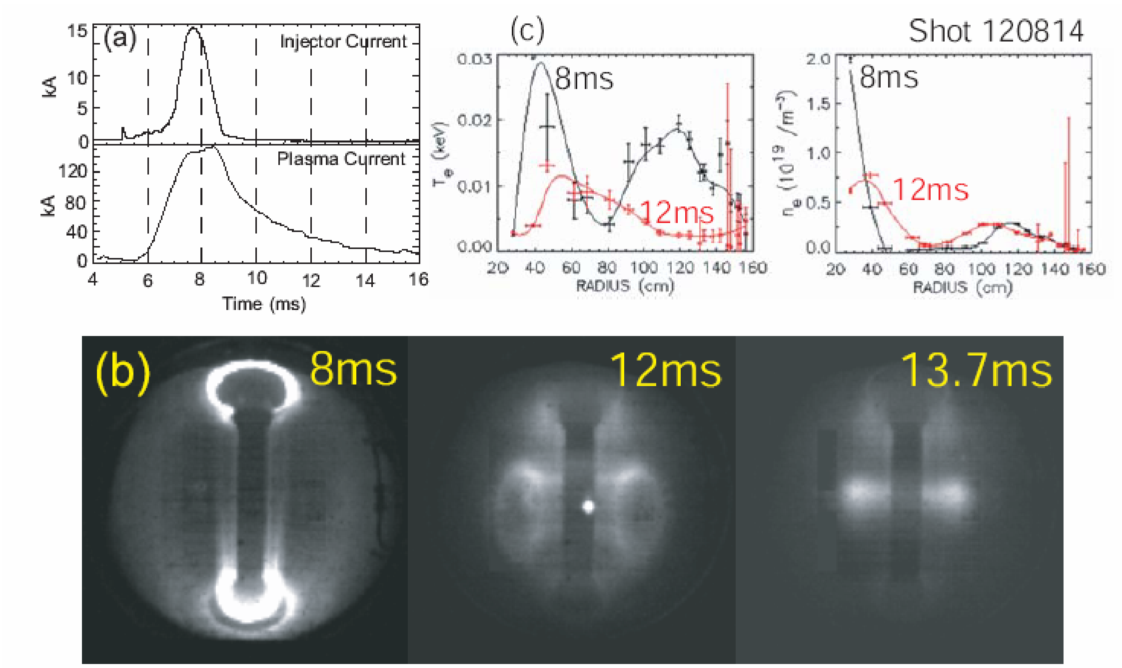

Figure 2: Shown are (a) the plasma and injector current traces (b) fast camera images and (c) the electron temperature and electron density profiles, at 8 and 12 ms from a CHI discharge in NSTX. The small bright glow near the middle of the vessel is light from a tungsten filament located near the wall inside the vessel.

The fourth requirement relates the maximum final toroidal plasma current I_p that can be produced to the energy available from the capacitor bank: $\frac{1}{2} L_p I_p^2 < E_{cap} = \frac{1}{2} CV^2$. The inductance of the toroidal plasma current on typical closed flux surfaces in NSTX is about 0.5 μH. For the present NSTX capacitor bank, the upper limit on the CHI produced current should be I_p = 400 – 600 kA. A final requirement is that the flux footprints on the CHI electrodes should be sufficiently narrow. On NSTX the lower divertor coils located outside the vessel are used to provide the injector flux shaping.

The operational sequence for transient CHI in NSTX involves first energizing the toroidal field coils and the poloidal field coils to produce the desired flux conditions in the injector region. A pre-programmed amount of deuterium is then injected into the cavity below the gap between the inner and outer lower divertor plates. The 18 GHz preionization power is applied and the 15 – 40 mF capacitor bank at up to 1.8 kV charging voltage is connected by an ignitron switch to the inner vessel and inner divertor plates, acting as the cathode, and the outer divertor plates and passive stabilizer plates, acting as the anode to form a discharge. After a programmed delay of 3 – 10 ms, when the plasma has expanded into the chamber and the toroidal plasma current is near its peak, the injector is short-circuited by a “crowbar” ignitron causing the injector current to decay rapidly. The plasma column detaches from the injector region to form closed flux, analogous to the detachment of a solar flare on the surface of the sun. Most of the divertor flux then reconnects the divertor electrodes again by the shorter path. A feature of CHI plasma generation using this method is that flux closure can be demonstrated unambiguously by the persistence of plasma current after the injector current has been reduced to zero. During these experiments, the NSTX central solenoid was disconnected from its power supply.

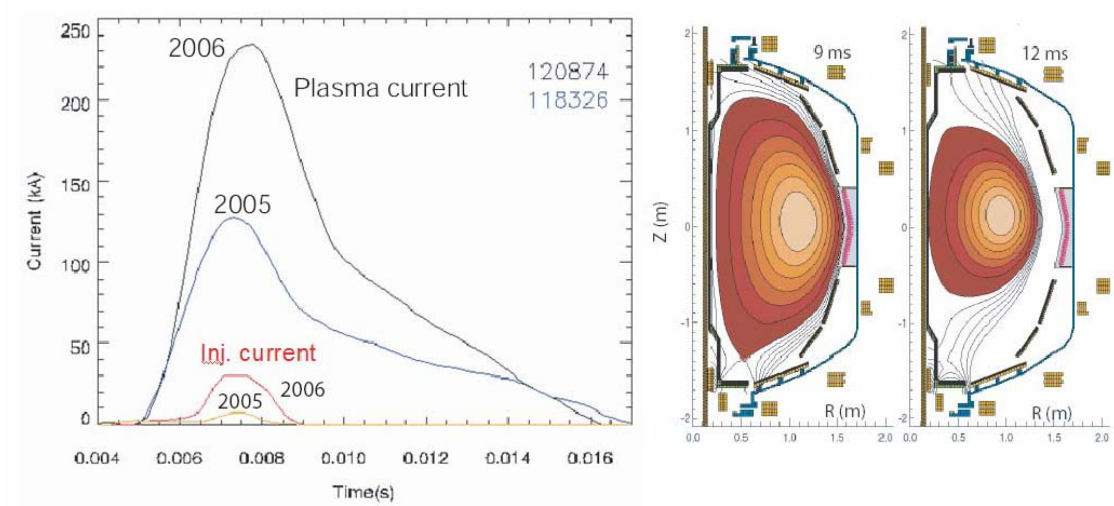

Figure 3: Plasma current injector current from discharges during 2005 and 2006. Operation at higher capacitor bank voltages and at higher values of the injector and toroidal flux resulted in the increase in the closed flux current to 160 kA during 2006. Equilibrium reconstructions at 9 and 12 ms for the higher current discharge (shot 120874) show the production of a closed flux equilibrium.

3. EXPERIMENTAL RESULTS

In Fig. 2, we show traces for the plasma current, the injector current and fast camera images at two different times during a typical CHI discharge. The discharge is initiated at 5 ms after which it rapidly grows to fill the vessel within about 2 ms. Note that the plasma current is amplified many times over the injector current. An absorber arc occurs around 8 ms, which increases the injector current to 17 kA. The absorber arc can be seen as the bright ring on the top of the camera image at 8 ms. For discharges that do not have an absorber arc, 2 kA of injector current is able to produce up to 120 kA of toroidal current, a current multiplication factor of 60. The image at 8 ms shows the plasma filling the vessel. Starting at about 9 ms, the discharge begins to disconnect from the injector electrodes after which the injector current falls essentially to zero while about 85 kA of toroidal plasma current remains. The 12 ms image shows an elongated dark region, which is surrounded by a brighter region, like usual visible-light images of tokamak plasmas. At 12 ms, the ring shaped plasma is clearly disconnected from both the injector and the upper divertor regions. As time progresses, the plasma further shrinks in size ending as a small diameter ring, as seen in the image at 13 ms. Since there is no injector current present after 9 ms, it is believed that the remaining plasma current is flowing in a closed magnetic flux configuration that decays on a resistive (L/R) timescale. In general, the Thomson scattering electron density and temperature profiles become less hollow as time progresses (see figure). This is expected since initially CHI drives current at the edge. After reconnection in the injector region, the current profile is expected to flatten, which should result in the profiles becoming less hollow. Taking the measured electron temperatures of about 15 – 20 eV and assuming Spitzer resistivity, and a typical plasma inductance of about 0.5 - 1 μH, results in a current-decay e-folding time on the order of 5 ms, which is consistent with the observation that the current persists for about

10 ms after the injector current has been reduced to zero. During these discharges, the NSTX central solenoid was disconnected from its power supply.

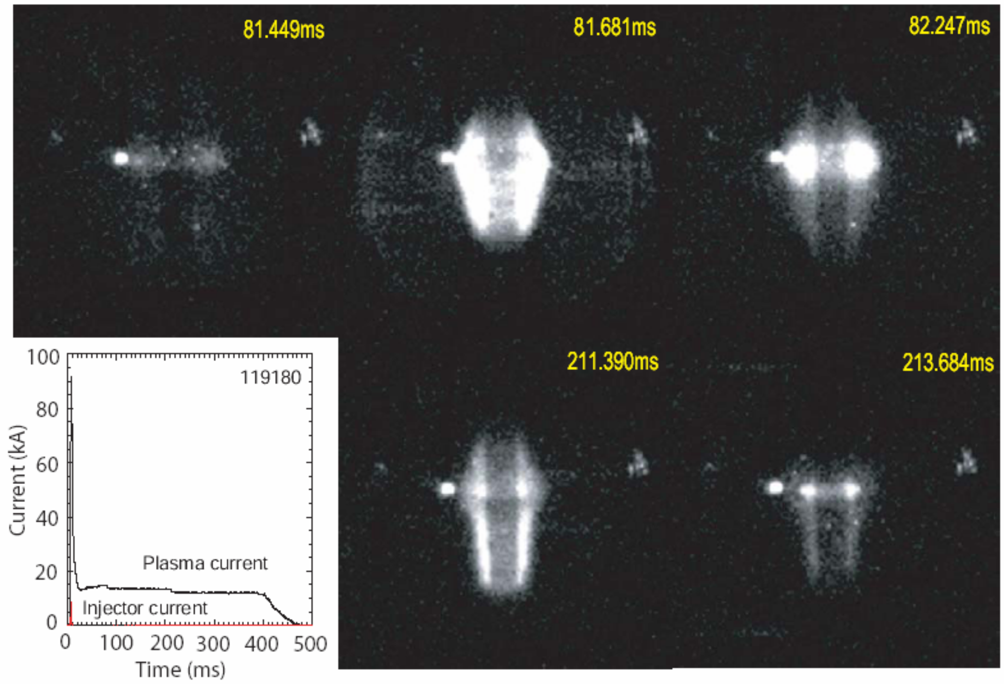

Figure 4: Fast camera images and plasma and injector current for a discharge that persisted for 400 ms. At 400 ms, the current in the poloidal field coils was ramped down to zero. At about 81 ms and 211 ms, the plasma discharge contacts the center stack resulting in visible emissions. Note that the plasma current drops after each contact with the wall. During the rest of the phase, the visible emission is very low, similar to that in the image at 81.449 ms

Equilibrium reconstructions from discharge 120874 are shown in Fig. 3 and confirm the conclusion that a region of closed flux has formed. The experimentally measured poloidal magnetic field at 40 sensors and poloidal flux at 44 flux loops distributed poloidally, are used in the computation of the Grad-Shafranov plasma equilibrium. The LRDFIT Grad-Shafranov equilibrium code [7] was used for these reconstructions. The code uses a circuit equation model of the plasma, vessel, and passive plate currents to constrain the equilibrium fits.

In other discharges, an example of which is shown in Figure 4, the plasma current shrinks in size following the normal pattern, then becomes diffuse and spreads along the center stack. Because the plasma discharge now expands to fill a much larger volume along the center stack, its apparent brightness decreases. The discharge then begins to reduce in elongation along the center column and becomes a faint small ring that persists for as long as the equilibrium coil currents are maintained. In the longest duration discharge, a 15 to 20 kA plasma discharge remained for nearly 400 ms. This discharge is fairly robust, as during the period form 40 to 400 ms, one can occasionally see the discharge contacting the center stack producing a bright flash, then fully recovering and continuing. During some of these events, the plasma current drops as shown in Fig. 4. In some of these discharges, one can also see faint filaments of plasma that circulate at larger major radius. The density of these plasmas is below the measuring resolution of the Thomson scattering system, which is about 1×10^{12} cm^{-3}.

4. DISCUSSION AND CONCLUSIONS

Using the method of transient CHI in NSTX, about 160 kA of closed flux toroidal current has been produced for an unambiguous demonstration of closed flux current generation in a large toroidal device. 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. Electron temperatures up to 20 eV have been measured in the plasma, similar to those seen on the HIT-II experiment. As time progresses, the measured profiles become less hollow, consistent with the expectations of CHI startup. Some discharges persist for very long durations, and seem to be limited only by the programmed decay in the vertical field. 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 of 60 between the injected current and the achieved toroidal current, compared to six in previous experiments, and (c) for the first time, fast time-scale visible imaging of the entire process that shows discharge formation, disconnection from the injector and the reconnection of magnetic field lines to form closed flux. These significant results indicate favorable scaling with machine size. Near term plans are to further increase the plasma current and to couple the CHI produced plasma to induction from the central solenoid. This would be followed by the application of up to 200 kW of microwave power to increase the electron temperature for coupling to other non inductive current drive methods.

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