Solenoid-free plasma startup in NSTX using transient CHI

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Abstract

Experiments in NSTX have now demonstrated the coupling of toroidal plasmas produced by the technique of coaxial helicity injection (CHI) to inductive sustainment and ramp-up of the toroidal plasma current. In these discharges, the central Ohmic transformer was used to apply an inductive loop voltage to discharges with a toroidal current of about 100 kA created by CHI. The coupled discharges have ramped up to >700 kA and transitioned into an H-mode demonstrating compatibility of this startup method with conventional operation. The electron temperature in the coupled discharges reached over 800 eV and the resulting plasma had low inductance, which is preferred for long-pulse high-performance discharges. These results from NSTX in combination with the previously obtained record 160 kA non-inductively generated startup currents in an ST or tokamak in NSTX demonstrate that CHI is a viable solenoid-free plasma startup method for future STs and tokamaks.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The favourable properties of the Spherical Torus (ST) confinement concept arise from its small aspect ratio [1]. Reactors based on the ST are projected to operate at very high values of the toroidal beta (>40%) and bootstrap current fraction (>90%) [2]. The capability of the ST to operate at high beta and high values of the bootstrap current fraction has been demonstrated in NSTX [3]. However, elimination of the central solenoid is essential for the viability of the ST concept, making solenoid-free plasma startup and non-inductive sustainment necessary for an ST based reactor or a component test facility. Solenoid-free plasma startup is also relevant to steady-state tokamak operation, as the central transformer coils of a conventional aspect-ratio tokamak reactor would be located in a high radiation environment but would be needed only during the initial discharge initiation

and current ramp-up phases. Removing the central solenoid provides greater flexibility in the selection of the aspect ratio and simplifies the reactor design.

Coaxial helicity injection (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 1980s [4]. At that time, it was generally believed that the development of non-axisymmetric MHD perturbations of the plasma equilibrium was needed for plasma startup using the CHI process in STs. This approach was initially investigated in NSTX and in several other STs. However, in a significant development during the past few years, it was shown that for the purpose of plasma startup, axisymmetric reconnection can produce a high quality startup equilibrium. This new method, referred to as *transient CHI*, was first demonstrated on the HIT-II experiment at the University of Washington [5]. The method has now been
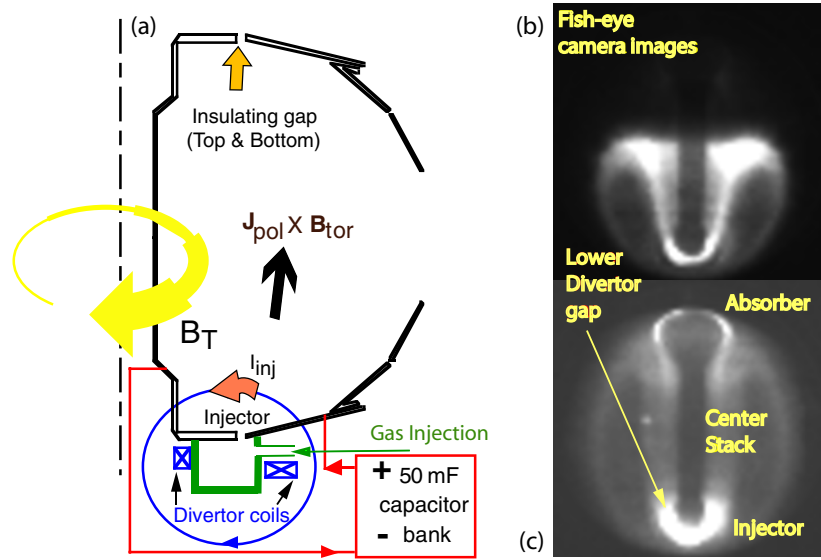
Figure 1. (*a*) On the left, is a line drawing showing the main components in NSTX required for plasma startup using the CHI method. Top-right (*b*) fast camera fish-eye image of the plasma during the early phase of plasma growth and (*c*) later in time after the CHI started discharge has filled the vessel.

successfully used on NSTX for a demonstration of solenoid-free plasma start up and successful coupling to subsequent inductive drive. The coupled discharges have ramped up to >700 kA. In addition, discharges that used 4 MW of neutral beam heating, transitioned into an H-mode demonstrating compatibility of this startup method with conventional high-performance H-mode operation.

2. Transient CHI startup in NSTX

NSTX has a major/minor radius of 0.86/0.68 m and a toroidal magnetic field at the nominal major radius up to 0.55 T. It is equipped with a central solenoid providing up to 0.7 Wb of inductive flux (double swung) which can generate plasma currents up to 1.5 MA. The outer poloidal field coils needed for equilibrium control are located about 0.5 m away from the plasma boundary. The entire plasma-facing boundary of NSTX is composed of graphite tiles. NSTX routinely applies conventional helium and deuterium glow discharge cleaning (GDC) as wall conditioning techniques. In the past, boronization of the plasma-facing surfaces has been used but in the last two years, lithium coating of the lower divertor plates has been investigated and developed as an alternative wall conditioning method.

As shown in figure 1, CHI is implemented by injecting current through the plasma from an external circuit along poloidal field lines that connect the lower divertor plates in the presence of a toroidal magnetic field. NSTX uses the lower divertor plates as the injector. The opposite end consisting of the upper divertor plates is referred to as the absorber. The $E \times B$ plasma drift is away from the injector region and into the absorber region. The initial poloidal field connecting the inner and outer divertor plates in the injector region is produced using the lower divertor coils, as shown in figure 1.

For successful application of the transient CHI process, five requirements need to be satisfied. 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 $I_{inj} = 2\psi_{inj}^2/(\mu_0^2 d^2 I_{TF})$, where ψ_{inj} is the poloidal flux at the injector insulating gap, I_{TF} is the total current in the toroidal field coil and d is the width of injector flux 'footprint' [4] on the electrodes. For NSTX conditions, injector currents as low as 1.5 kA satisfy this condition.

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 and 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 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, for deuterium gas, about 120 eV per ion is needed for ionization and to increase the plasma temperature to 20 eV. This is generally a more difficult requirement to satisfy, as gas breakdown is easier at higher pressures where more energy is then required. On NSTX it has been possible to decrease the total amount of injected deuterium to ~2 Torr L, which is similar to the amount of gas normally used for inductive startup. Substantial reduction in the amount of gas needed for breakdown was realized by injecting it in a cavity below the gap between the lower divertor plates. Initial experiments at modest voltages, ~1 kV, on the capacitor bank benefited from a 10 kW, 18 GHz electron cyclotron heating (ECH) pre-ionization source. However, at capacitor bank charging voltages of 1.5 kV and higher, reliable gas breakdown was possible without the use of ECH. During 2008 ECH pre-ionization was not used in any of the CHI started discharges.

The fourth requirement relates the maximum final toroidal plasma current I_p that can be produced to the energy available from the capacitor bank: $0.5L_pI_p^2 < E_{cap} = 0.5CV^2$. The inductance of the toroidal plasma current on typical equilibrium in NSTX is about 0.5 μH. For the present NSTX capacitor bank, the upper limit on the CHI produced toroidal plasma current is about 500 kA. The 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.

For transient CHI discharge initiation, the toroidal field coils and the poloidal field coils needed to produce the desired flux conditions in the injector region are first energized. A pre-programmed amount of deuterium gas is then injected into the cavity below the gap between the inner and outer lower divertor plates. The 5–45 mF capacitor bank charged at up to 1.7 kV is connected by an ignitron switch to the lower divertor plates. The inner vessel and inner divertor plates act as the cathode, and the outer divertor plates and passive stabilizer plates act as the anode. This initiates the CHI 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 an ignitron causing the injector current to rapidly decay. This produces reconnection of the magnetic field near the lower divertor plate region and causes the plasma column to detach from the injector region to form closed flux. An aspect 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 recent experiments in NSTX, induction was then applied to the closed-flux plasma equilibrium by ramping the current in the central solenoid to investigate coupling of the CHI-produced current to conventional inductive operation.

3. Experimental results

Figure 2 shows a discharge in which a CHI discharge is started with the central solenoid disconnected from its power supply. A 15 mF capacitor charged to 1.7 kV was used in this experiment to drive the injector current. In this discharge approximately 3 kA of injector current produces nearly 120 kA of plasma current, so the current multiplication, defined as the ratio of the plasma current to injector current, is about 40. The highest current multiplication obtained in NSTX CHI discharges is 70. At 10 ms, with nearly zero injector current, about 60 kA of toroidal plasma current remains on closed field lines. After the CHI injector current is reduced to zero, the CHI capacitor bank is no longer driving the plasma load. The only plausible explanation for the remaining toroidal plasma current is the creation of a closed-flux equilibrium that then decays on an L/R time scale. The highest amount of closed-flux current produced in NSTX CHI discharges is 160 kA, which is a world record for non-inductively generated closed-flux current in an ST or tokamak. In [6], we show equilibrium reconstructions for CHI-produced discharges based on fitting to external magnetic measurements, which demonstrate the presence of closed-flux surfaces during the decay phase of the discharge.
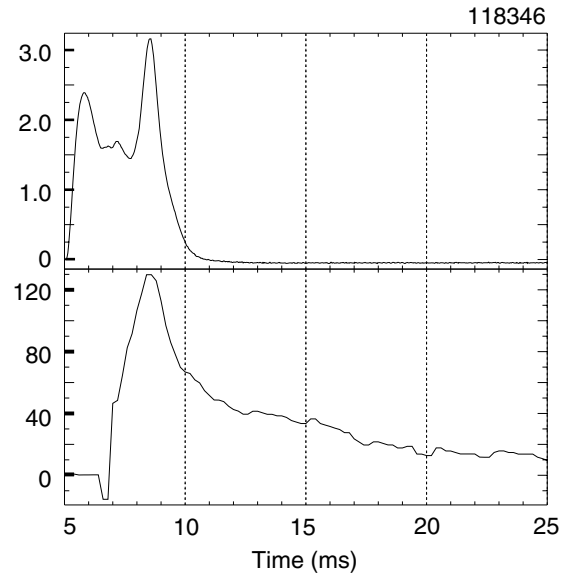

Figure 2. Injector and plasma currents for a discharge in which the central solenoid was disconnected from its power supply. Note that the magnitude of the plasma current is many times that of the injector current. After the injector current is reduced to near zero, the persisting plasma current indicates the presence of a decaying closed-flux equilibrium.

In figure 3(*a*), we show traces for the injector current, the plasma current and the applied inductive loop voltage for a CHI started discharge, similar to that shown in figure 2 that was then coupled to induction. In this discharge approximately 3 kA of injector current produces about 100 kA of toroidal current initially. During the decay phase of this current, induction is applied from the central solenoid by ramping its current from zero with a rectifier power supply with an open-circuit voltage of 4 kV. The decrease in the applied loop voltage over time is due to resistance in the central solenoid circuit. The external poloidal field coil currents needed for equilibrium are pre-programmed during the first 40 ms of the discharge. After that the standard NSTX plasma control system [7] is used to control the plasma radial and vertical position, using real-time data from external flux loops and magnetic probes. This causes the decaying plasma current to ramp up, reaching a peak value of 700 kA in this case. In this discharge, starting at about 40 ms, neutral beams are also injected at a power of 4 MW to heat the plasma. During the NB heating, the discharge transitions into an H-mode at 160 ms. Evidence of the H-mode is the characteristic drop in divertor D_α emission (figure 3(*a*)) and the development of a broad electron density (N_e) profile measured by the Thomson scattering diagnostic (figure 3(*b*)). Figure 3(*b*) also shows the electron temperature (T_e) from Thomson scattering and the ion temperature (T_i) profile from charge-exchange recombination spectroscopy (CHERS) for the discharge after the transition into H-mode. At 180 ms, the discharge has low internal inductance $l_i = 0.64$, central safety factor $q(0) = 1.4$, elongation $\kappa = 2.1$ and an average triangularity $\delta = 0.47$. The fact that a CHI initiated discharge is able to transition to a discharge that has features suitable for a high-performance long-pulse operation bodes well for the application of this startup method to future machines.
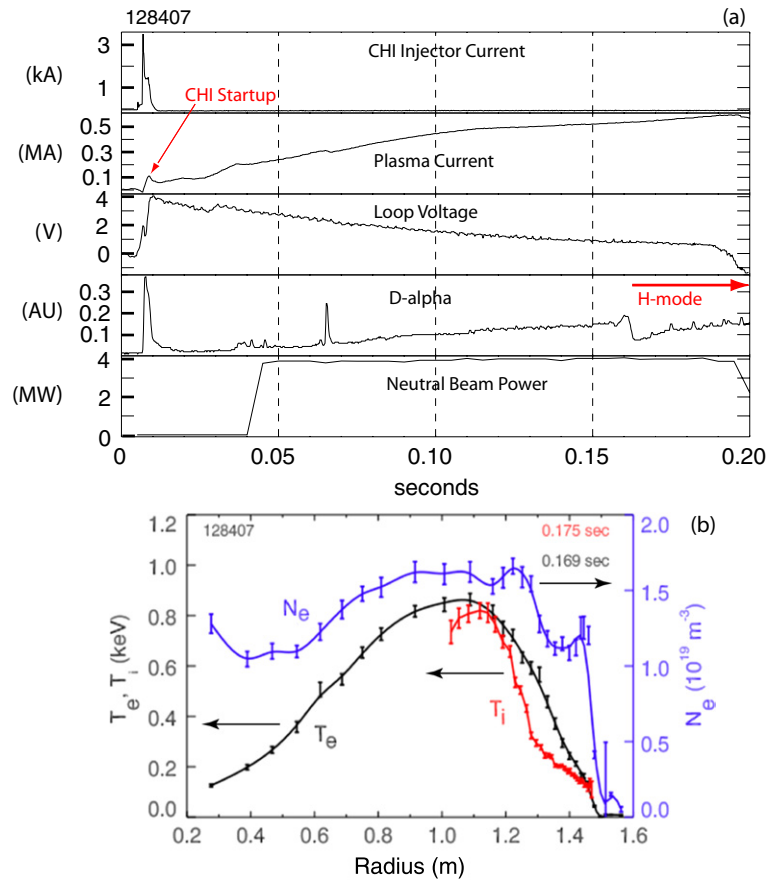
Figure 3. (*a*) Traces from a CHI started discharge that was coupled to induction using the central solenoid. Shown are the CHI injector current, the resulting CHI-produced plasma current, the pre-programmed loop voltage, the divertor D_α signal and the applied neutral beam power. (*b*) Shown are the electron temperature and density profiles from a Thomson scattering diagnostic soon after transition to H-mode and the ion temperature profile from a CHERS diagnostic. Note the steepening in the edge density gradient during the H-mode phase.

In this discharge the loop voltage peaks about 0.9 ms after the time of peak plasma current. Although the timing of the loop voltage application has been varied during these coupling studies, a detailed scan of the timing of the loop voltage application with the peak in the plasma current has not yet been conducted in optimized discharges. In studies so far, further delaying the time of inductive ramp reduces the coupling to induction. Moving it earlier in time has not shown a dramatic improvement, but those scans were conducted in un-optimized discharges. After higher startup current optimized discharges are obtained, the timing of the loop voltage will be studied in more detail to reduce the drop in plasma current after the application of the inductive ramp.

The first attempts to add inductive drive to CHI initiated discharge resulted in no increase in the plasma current. However, in these discharges there was a significant increase in the O II emission when the loop voltage was applied. It was not until extensive conditioning was performed in the form of D_2 GDC and electrode discharge conditioning that the plasma current was able to be increased by induction. Evidence for the need to condition the walls and/or divertor plates is shown in figure 4. Shots taken with 1, 2, and 3 capacitor banks (5, 10 or 15 mF) in the CHI system differed primarily in the intensity of the low-*Z* (C and O) impurity emission. The plasma current traces show that as the size of the capacitor bank is increased, the magnitude of the attained plasma current increases. Using 1 capacitor module (5 mF), the maximum in the plasma current is only 40 kA, with 3 modules (15 mF), the attained plasma current increases to 140 kA. However, as the magnitude of the plasma current increases, its rate of increase during the subsequent inductive phase actually decreases. The discharge that uses three capacitors has the fastest current decay rate immediately after the CHI pulse and does not couple well to induction, even though the input power is highest for this discharge. This behaviour is understood by examining the filter scope signals that show the oxygen and carbon line radiation signals in the upper and lower divertor region. These signals increase as the magnitude of the injector current increases. At a higher level of injector current more of the electrode surface contaminants are liberated into the plasma and contribute to increased energy losses during startup. The discharge with three capacitors also had increased levels of absorber arc current, which occurs when part of the injector current bridges the upper divertor gap and flows along the upper insulator surface, thereby producing additional contaminants from the absorber region. In principle, as demonstrated on HIT-II [5], the absorber arc can be minimized or eliminated through control of the magnetic field pattern in the upper divertor region to minimize the amount of poloidal flux that connects the upper divertor plates.

As seen in figure 4, with one and two capacitors, the line radiation signals do not change much, but with two capacitors
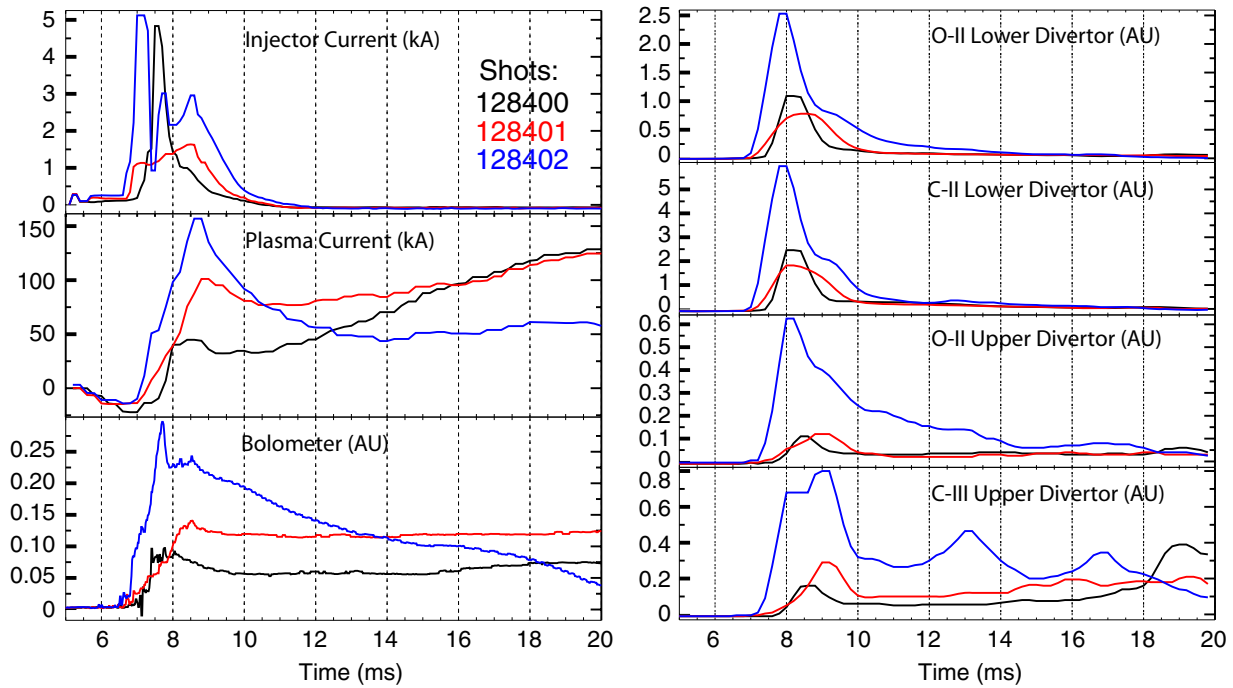
Figure 4. Left—injector and plasma current traces for discharges operated with 5, 10 and 15 mF capacitor banks and the radiated power as measured by a wide-angle bolometer. Right—shown are the resulting line radiation signals from oxygen and carbon in the injector and absorber regions. Shot 128400 used a single capacitor module (5 mF, 7.2 kJ), shot 128401 used two capacitors (14.4 kJ initial stored energy in the capacitors) and shot 128402 used three capacitors (21 kJ).

there is a small increase in the signal from a wide-angle bolometer with a view over most of the plasma below the mid-plane of NSTX. Both the one and two capacitor cases couple well to induction, but the rate of current increase is higher for the one capacitor case. With three capacitors, however, the spectroscopic signals are significantly elevated and so is the radiated power signal. As demonstrated in experiments on HIT-II [5], CHI discharges cannot couple to induction if the radiated power approaches the input Ohmic power. For these plasmas with about 3–4 V of applied loop voltage and a plasma current of 100 kA, the input Ohmic power is less than 300–400 kW during the inductive coupling phase. Thus it is essential that during the startup phase, either (a) the radiated power be lower than the input Ohmic power, or (b) some form of auxiliary heating system such as ECH be used to heat the target plasma. During startup, because the plasma temperature is less than 20 eV, the dominant radiation comes from low-Z impurities such as carbon and oxygen. For the graphite divertor plates used in NSTX, it is essential that surface contaminants be significantly reduced. On HIT-II, which used graphite for the centre 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 [5]. 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 saving of inductive flux has not yet been demonstrated in NSTX. For the near term, low-Z impurity radiation could be reduced on NSTX through an extensive high-current electrode discharge cleaning effort to remove impurities, notably water, from the graphite tiles in the injector. Additionally, newly installed coils in the upper divertor region will be used to eliminate the absorber arcs which also contribute

impurities. Finally, a 350 kW ECH system capable of heating the startup plasma will be implemented on NSTX during 2010. With these techniques, NSTX discharges should be able to achieve reductions in the inductive flux consumption. It is useful to note that in HIT-II nearly the entire CHI started current is retained in the subsequent inductive ramp [5]. If the impurity levels in NSTX are sufficiently reduced, then approximately 34 mWb of central solenoid flux would be saved for a startup current of 100 kA and about 87 mWb would be saved for a startup current of 300 kA. In NSTX for zero pre-charge in the central solenoid 350 mWb is available from the central solenoid for current ramp-up.

However, it is more important to note that for a reactor that has no central solenoid, the essential requirement for startup is that solenoid-free started currents be capable of coupling to an alternate non-inductive current drive system, and this can be made easier using additional heating sources. Additionally, future machines are likely to use metal rather than carbon over a large part of the divertor plates to reduce tritium retention, and this may reduce radiation from low-Z impurities during plasma startup.

Recently the possible benefits for CHI discharges of lithium coating applied to the lower divertor plates were also tested. During these experiments, lithium was evaporated from two ovens mounted at the top of the vacuum vessel onto the lower divertor region at a rate of 10 mg min^{-1} for 10 min prior to the initiation of a CHI discharge. The evaporator system is described in the 2008 IAEA Fusion Energy Conference proceedings [8]. The immediate benefit of lithium was to make the CHI started discharges more reproducible. This is probably because of the fact that lithium has a much lower ionization energy ($\sim$5 eV) than deuterium (13 eV), and can act
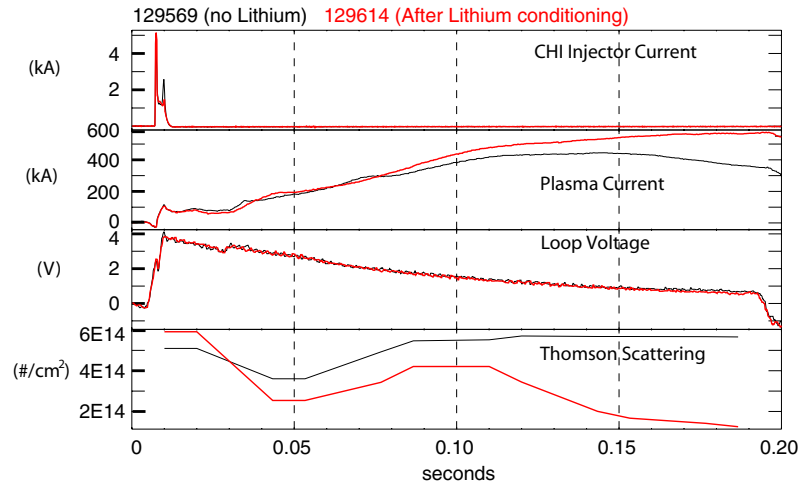
Figure 5. Comparison of discharges with and without the application of a lithium evaporative coating on the lower divertor plates in NSTX. In the discharge with Li conditioning, the plasma density significantly decreases over time.

as a pre-ionizing source for the bulk of the injected deuterium. It is useful to note that an effort to initiate CHI discharges in helium (ionization energy ∼25 eV) was much more difficult. The application of lithium reduces recycling of deuterium at the electrode surfaces, and it was anticipated that this would lower the density of the CHI-produced plasma. At lower density the plasma should heat up to a higher temperature, which should reduce the L/R decay rate and thereby increase the current at the time that induction was applied. A similar effect was seen on the HIT-II experiments when titanium gettering was employed as a wall conditioning technique. However, despite the benefit of lithium conditioning to the reproducibility of CHI startup in NSTX, the magnitude of the initial plasma current produced by CHI did not increase with the use lithium. The reason may be that the amounts of lithium used in present experiments were too small to observe the pumping effect on the fast time scale of the plasma initiation. However, on a longer time scale wall pumping was observed as shown in figure 5, which compares two CHI started discharges with and without the application of lithium, but similar in other respects. After coupling to induction, the discharge with lithium has a much lower density and reaches a higher plasma current.

4. Summary and conclusions

Using the method of transient CHI in NSTX, 160 kA of closed-flux toroidal current has been produced. Now, for the first time in NSTX, CHI started discharges have been successfully coupled to induction to show compatibility between CHI started discharges and the conventional inductive approach. While results similar to this have been previously demonstrated on the smaller HIT-II experiment, this is the first such demonstration on a large ST with a poloidal field configuration more prototypical of a compact ST reactor such as the Component Test Facility (CTF). Another significant new result

is achieving a current multiplication factor up to 70, which is an order of magnitude larger than achieved in previous smaller experiments, and suggests a favourable scaling of the technique with machine size. The transitioning of the CHI-produced discharges in NSTX to a high confinement H-mode with low plasma inductance demonstrates the potential for the application of this method to future machines.

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