Non-inductive Plasma Start-up in NSTX Using Transient CHI

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Abstract. Transient Coaxial Helicity Injection (CHI) in the National Spherical Torus Experiment (NSTX) has generated toroidal current on closed flux surfaces without the use of the central solenoid. When induction from the solenoid was added, CHI initiated discharges in NSTX achieved 1 MA of plasma current using 65% of the solenoid flux of standard induction-only discharges. In addition, the CHI-initiated discharges have lower density and a low normalized internal plasma inductance of 0.35, as desired for achieving advanced scenarios. The Tokamak Simulation Code (TSC) has now been used to understand the scaling of CHI generated toroidal current with variations in the external toroidal field and injector flux. These simulations show favourable scaling of the CHI start-up process with increasing machine size. The TSC code is also now starting to be used for full discharge simulation, which includes start-up with CHI and subsequent current ramp-up using neutral beams. These results from NSTX imply a current generation potential in excess of 400 kA in the NSTX-U currently under construction.

1. Introduction

Tokamaks and spherical tokamaks (STs) have relied on a central solenoid to generate the initial plasma current and to sustain that current against resistive dissipation. However, a central solenoid cannot be used for plasma current sustainment indefinitely. The inclusion of a central solenoid in a tokamak for plasma start-up alone limits the minimum aspect ratio and adds cost and complexity. For reactors based on the ST concept, elimination of the central solenoid is necessary so alternate methods for plasma start-up would be needed.

CHI research on NSTX initially used the method of *driven* or *steady-state* CHI for plasma current generation [1]. Although substantial toroidal currents were generated using the steady-state approach, it was found that these discharges could not be successfully ramped up in current when induction was applied. However, complementary experiments on the HIT-II experiment at the University of Washington then demonstrated that the method of *transient* CHI could generate high-quality plasma equilibrium in a ST that could be successfully coupled to inductive drive [2]. Since that discovery, the transient-CHI method has been successfully applied to NSTX for solenoid-free plasma start-up followed by inductive ramp-up [3]. These coupled discharges have now achieved toroidal currents >1 MA using significantly less inductive flux than standard inductive discharges in NSTX.

2. Experimental results

CHI is implemented in NSTX by driving current along field lines that connect the inner and outer lower divertor plates as shown in Fig. 1 and described in detail in References [1-3]. In

NSTX the inner vessel and lower inner divertor plates are the cathode while the outer divertor plates and vessel are the anode. Prior to initiating a CHI discharge the toroidal field coils and the lower divertor coils are energized. The lower divertor coils produce magnetic flux linking the lower inner and outer divertor plates, which are electrically isolated by toroidal insulators in the vacuum vessel. A programmed amount of gas is then injected into the vacuum chamber and voltage is applied between these plates, which ionizes the gas and produces current flowing along magnetic field lines connecting the plates. In NSTX, a 5 to 30 mF capacitor bank charged to 1.7 kV provides this current, called the injector current. As a result of the applied toroidal field, the field lines joining the electrodes wrap around the major axis many times so the injector current flowing in the plasma creates a much larger toroidal component, typically by a factor 10 – 50 at the peak of the injector current in NSTX.

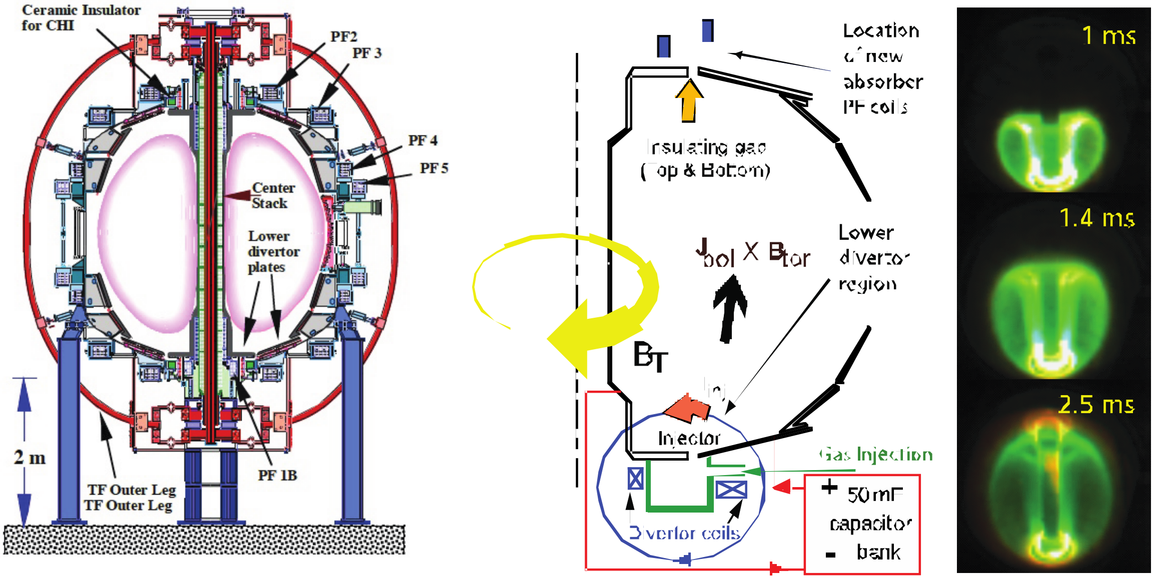

Figure 1: Shown are (left) drawing of the NSTX machine, (middle) cartoon of CHI start-up and (right) fast camera images of an evolving CHI discharge 1ms, 1.4ms and 2.5ms after discharge of the CHI capacitor bank.

Significant improvement in the performance of CHI discharges in NSTX were achieved by reducing the low-Z impurities, mainly oxygen and carbon in the initial electrode-driven discharge. Reference [3] describes this work in detail so the methods are briefly summarized here. The lower divertor plates, which are used as the CHI electrodes were initially cleaned using an extended electrode discharge. The CHI system itself was used for this purpose by running many discharges at high injector current but with greatly increased injector flux connecting the lower divertor plates. By maintaining the injector current below the level required (by MHD considerations) for ejecting the flux, the discharge was maintained near the lower divertor plates. This cleaning was followed by coating the lower divertor plates with lithium from a pair of evaporator ovens mounted at the top of the vacuum chamber, as described in Reference [4]. Finally, during the CHI discharges, two poloidal field coils located in the upper divertor region were energized to provide a "buffer" flux to reduce contact of the growing CHI discharge with the upper divertor electrodes [3]. Without this buffer flux, the growing CHI discharge could contact the upper divertor plates. This usually generated an arc between the plates, which injected low-Z impurities into the CHI discharge, causing it to become more resistive which rapidly consumed the poloidal flux in the plasma.

Detailed results on the coupling of CHI started discharges to induction are described in recent references [5,6]. The results on the reduction in central solenoid flux required to reach normal plasma current are briefly summarized here. In Fig. 2 we are comparing the plasma current trace for a CHI started discharge ramped up by induction to a standard discharge initiated and ramped up by induction only. The inductive-only discharge is from the NSTX database, assembled over 10 years of operation that reached 1 MA in a shorter time than other L-mode discharges. At 132 ms the CHI-started discharge consumes a total of 258 mWb of central solenoid flux to ramp up to 1 MA. At this time the reference inductive-only discharge gets to about 0.7 MA and it does not reach 1 MA until 160 ms, by which time 396 mWb of central solenoid flux had been consumed. Typical L-mode discharges in NSTX require at least 50% more inductive flux than discharges assisted by CHI.

Fig. 2 shows that these plasmas have both a very high elongation of $\kappa \approx 2.6$ and very low internal inductance $l_i \approx 0.35$ from the start of the discharge. The CHI-initiated plasmas are relatively free of MHD activity despite having low density, which has previously been associated with increased instability during normal inductive start-up. The lower internal inductance of CHI generated discharges is associated with the formation of a hollow electron temperature profile, which is a characteristic of the CHI start-up process which causes more of the current to flow in the outer region. This, in turn, increases the elongation of the plasma cross-section because the current flowing in the plasma is effectively closer to the currents in the external equilibrium control coils. Many advanced operating modes for tokamaks strive to maintain a hollow current profile throughout the discharge both to reduce thermal transport and to maintain macroscopic plasma stability. That CHI is able both to provide an initial current profile similar to that which is achieved in conventional tokamaks through the use of high-power auxiliary heating, and to produce lower densities than achievable with conventional inductive startup should benefit advanced scenario operations in NSTX-U.

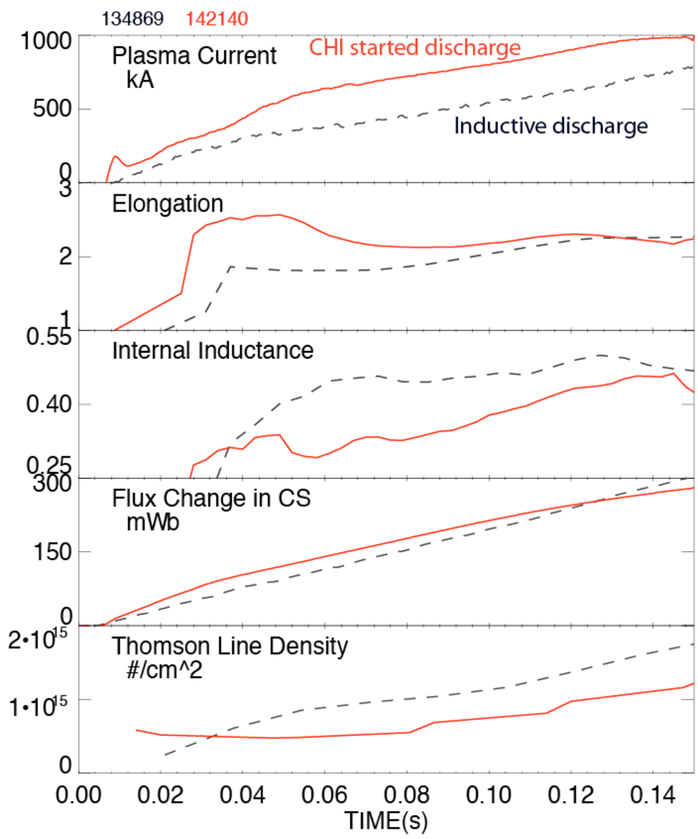

Figure 2: Comparison of time traces for discharges initiated with and without CHI start-up.

3. TSC Simulations

TSC is a time-dependent, free-boundary, predictive equilibrium and transport code [7, 8]. It has previously been used for development of both discharge scenarios and plasma control systems. It solves fully dynamic MHD/Maxwell's equations coupled to transport and circuit equations. The device hardware, coil and electrical power supply characteristics are provided as input. It models the evolution of free-boundary axisymmetric toroidal plasma on the resistive and energy confinement time scales. The plasma equilibrium and field evolution equations are solved on a two-dimensional Cartesian grid. Boundary conditions between plasma/vacuum/conductors are based on poloidal flux and tangential electric field being continuous across interfaces. The circuit equations are solved for all the poloidal field coil systems with the effects of induced currents in passive conductors included. Currents flowing in the plasma on open field lines are included, and the toroidally symmetric part of this "halo current" is computed. For modelling CHI in NSTX, the vacuum vessel is specified as a conducting structure with poloidal breaks at the top and bottom across which an electric potential difference is applied from which TSC calculates the injector current using a model for the resistivity of the "halo" plasma. This circuit, however, contains a sheath resistance at each electrode which is difficult to model. Since for the purposes of this study, it is the injector current and flux that are important, we adopted the modelling strategy of adjusting the injector voltage in order to match the measured current rather than simply applying the measured injector voltage. The simulation used the poloidal field (PF) coil current time histories measured in the experiments.

TSC simulations of NSTX transient CHI discharges have successfully demonstrated current persistence [9], that is the toroidal current persisting after the injector current has been reduced to zero. This generation of closed flux is the result of an effective (positive) toroidal loop voltage induced by the changing poloidal flux on the open field lines as the injector current is reduced to zero. Reference [11] provides additional details showing consistency with earlier theoretical predictions [10]. It also shows that CHI scaling with toroidal field is favourable for larger machines so that peak plasma currents on the order of 600 kA could be generated using the injector poloidal flux capability of the present NSTX if both the toroidal field were increased to 1 T and a similar amount of injector current could be achieved. The higher toroidal field allows more poloidal flux to be produced in the plasma at the same level of injector current.

We have now conducted the first simulations of a fully non-inductive start-up with CHI and subsequent non-inductive current ramp-up using neutral beams in support of planned experiments on NSTX-U. The CHI discharge is initiated by TSC as described in Reference [11], and a 400 kA closed-flux target is generated. The first step involves current driven by the external injector circuit on purely open field lines. After this discharge fills the vessel, the applied CHI voltage is rapidly reduced. The resulting rapid decrease in the injector current and its poloidal flux induces within the open field line CHI discharge, a positive loop voltage that causes the generation of closed field lines carrying toroidal current. At the onset of flux closure a second step in the simulation is initiated. This continuously solves for the plasma boundary, including locating the divertor X-point and begins solving the flux surface averaged transport equations. This phase begins 17 ms after the CHI discharge is first initiated.

For these simulations, the initial electron temperature for the CHI discharge is 100 eV. This is a reasonable starting value based on other simulations that show that 1 MW of 28 GHz RF heating power could rapidly increase the electron temperature of a CHI-like discharge to over 100 eV. The initial electron density is assumed to be 3 x 10^{18} m^{-3}, similar to the densities obtained during CHI start-up in NSTX as shown in Fig. 2. In the simulation, the initial plasma internal inductance is also below 0.5, consistent with that calculated by EFIT for the CHI discharge in NSTX shown in Fig. 2. However, at about 250 ms in the simulation, l_i increases to about 1.2 but by 500 ms it falls to about 0.55 and remains there for the rest of the discharge. This transient is probably because the CHI discharge is rapidly decaying in current. It may also be related to the very low level of confinement (less than 1ms during this period) resulting from the transport model used in these simulations.

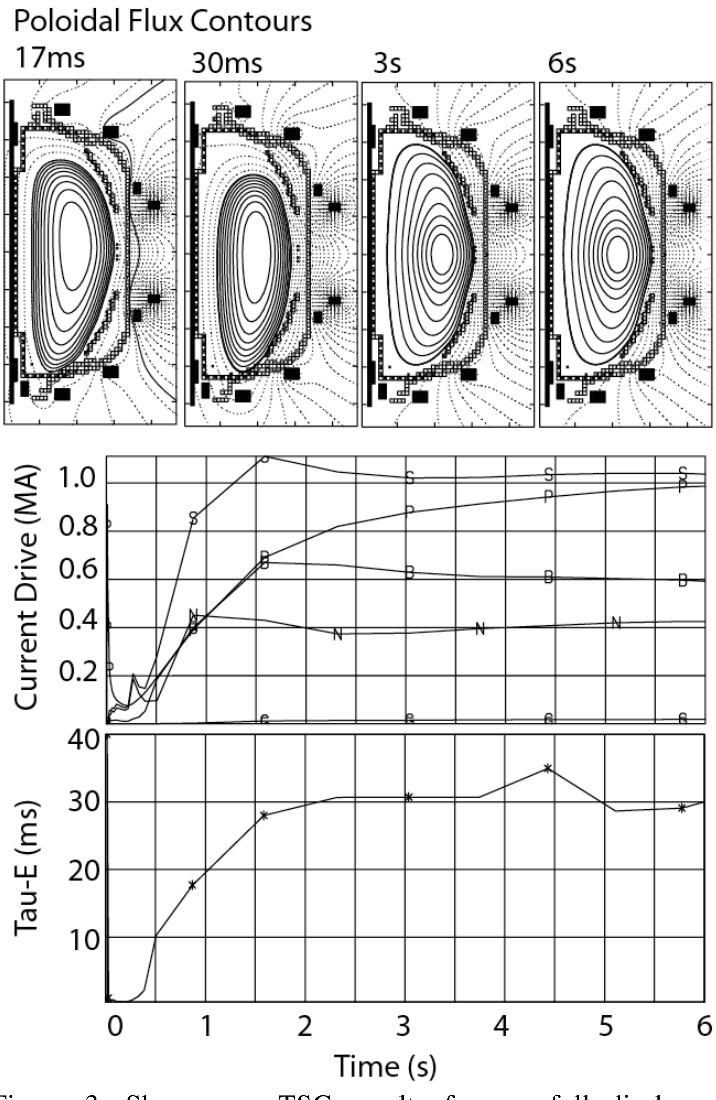

Figure 3: Shown are TSC results from a full discharge simulation that involves plasma start-up using CHI and current ramp-up using NBI and bootstrap current overdrive. Top frame: Shown are the poloidal flux contours at 17ms, during the end of the CHI-phase, at 30ms during the coupling phase and at 3 and 6 seconds during the current ramp-up phase. Middle frame: The different components of current drive. N: Neutral beam, B: Bootstrap, P: Plasma current and S: Sum of current drive terms. Bottom frame: The energy confinement time calculated with respect to input power.

At 17 ms, horizontal position control is implemented and at 40 ms vertical position control is used to vertically center the highly up/down asymmetric CHI plasma. The electron transport is adjusted to keep the energy confinement time at about 30 ms, consistent with energy confinement times in neutral beam heated NSTX discharges. During the low density phase of the discharge the RF power is increased to 2.5 MW. This is assumed to be from a combination of 0.5 MW absorbed ECH power and 2 MW of absorbed HHFW power. After that 2 MW of HHFW power is retained in these simulations. Neutral beams are added in increments to keep the current over drive at acceptable levels, as TSC is not capable of handling the formation of current "holes" where the toroidal current density drops to zero. After the current has built up to sufficient levels, both the density and neutral beam power are ramped-up. Fig. 3 shows the results from this first evolving discharge, which at 6s reaches 1 MA of plasma current.

4. Summary and Conclusions

The application of CHI on NSTX and on HIT-II combined with recent simulations with the TSC code has revealed many important aspects of CHI physics and its application to future machines, particularly the NSTX-U [12] . The key results, not all of which are covered in this paper but are described in the supporting references, are briefly summarized below.

- NSTX and HIT-II, two machines of quite different size (NSTX plasma volume is 30 times that of HIT-II), have both achieved significant levels of start-up current through CHI.
- On NSTX, considerable improvements to CHI discharge performance were enabled by developing methods to reduce the low-Z impurities in the initial electrode-driven discharge. As a result, 300 kA of start-up current has been produced using just 29 kJ of stored capacitor bank energy (>10A/J). When induction was applied to these CHI started discharges, they required about 40% less inductive flux from the solenoid to reach 1 MA plasma current than inductive-only discharges.
- The scaling to larger machines with higher toroidal field is quite favorable: NSTX achieves 10 times the current multiplication factor of HIT-II.
- The CHI generated plasmas on NSTX have desirable properties including low inductance and electron density and high elongation needed for subsequent non-inductive sustainment utilizing the bootstrap current and NBI and RF waves.
- Simulations with the TSC code show agreement with the theoretical prediction for CHI as it is scaled to larger machines. These simulations indicate the importance of an auxiliary electron heating system to boost the temperature of CHI discharges.
- Simulations with the TSC, show that CHI has the potential to generate significant initial current in NSTX-U suitable for ramping up the current with other forms of non-inductive current drive.
- The TSC shows that the second more tangential neutral beams in NSTX-U should be capable of ramping up the current of a CHI targets to 1 MA levels, provided that the temperature of the CHI discharges can be increased to a few hundred eV level through the use of an auxiliary heating system such as ECH and or improved vessel conditioning methods.

The NSTX is now undergoing a major upgrade, to NSTX-U, to increase the capabilities of its toroidal and poloidal field coils and to add a second more tangentially injecting neutral beam line. Analysis of the NSTX results shows that the amount of closed-flux current generated by CHI is closely related to the initially applied injector flux [5]. On NSTX-U the available injector flux is about 340 mWb, considerably exceeding the 80 mWb in NSTX. The modelling projects that it should be possible to generate over 400 kA of closed-flux current with CHI in NSTX-U. At this current, the second more tangentially injecting neutral beam should be capable of providing sufficient current drive to ramp-up the plasma current. TSC simulations show that CHI could be an important tool for non-inductive start-up in next-step STs and quite possibly for tokamaks as well.

This work is supported by U.S. DOE Contracts DE-AC02-09CH11466 and DE-FG02-99ER54519 AM08.

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