

Non-inductive Plasma Current Start-up in NSTX using Transient CHI and subsequent Non-inductive Current Ramp-up Scenario in NSTX-U

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Transient Coaxial Helicity Injection (CHI) in NSTX has generated closed flux plasma currents up to 200 kA. When induction from the central solenoid is then added to these discharges they achieved 1 MA of plasma current using 65% of the solenoid flux of standard induction-only discharges. The CHI-initiated discharges have low plasma density and normalized internal plasma inductance of 0.35 through the inductive ramp, typical of advanced scenarios planned for future STs. An important objective of the NSTX-U program is to ramp-up CHI-started discharges non-inductively to the steady-state current sustainment levels. In support of this goal, the Tokamak Simulation Code (TSC) has been used to conduct initial simulations of a full discharge modeling in which a CHI-started discharge is ramped-up in current to 1 MA using a combination neutral beam current drive and bootstrap current overdrive.

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 during steady-state operation. Elimination of the central solenoid may be necessary for an ST based Fusion Nuclear Science Facility (FNSF), and it can also simplify the tokamak concept by removing an expensive component and providing greater access to aspect ratio optimization. Plasma start-up using transient CHI is one means to achieve this.

CHI [1] research on NSTX initially used the method of *driven* or *steady-state* CHI for plasma current generation [2]. 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. Supporting experiments on the HIT-II experiment at the University of Washington demonstrated that the method of *transient* CHI could generate high-quality plasma equilibrium in a ST that could be coupled to inductive drive [3]. Since then the transient-CHI method has been successfully applied to NSTX for solenoid-free plasma start-up followed by inductive ramp-up [4]. These coupled discharges have now achieved toroidal currents >1 MA using significantly less inductive flux than standard inductive discharges in NSTX.

Implementation of CHI in NSTX: CHI is implemented in NSTX by driving current along field lines that connect the inner and outer lower divertor plates as described in detail in References [1-4]. In NSTX the inner and outer vessel components are electrically separated by two toroidal insulators. The inner vessel and the 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. 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 develops a much larger toroidal component. Significant improvements 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 plasma as described in Reference [5].

Figures 2 and 3 in Reference [4] compares traces for CHI started discharges that were followed by inductive ramp-up to a standard discharges on NSTX initiated and ramped up by induction only. The inductive-only discharges are 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 discharges get to about 0.7 MA and they do not reach 1 MA until 160-190 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 to reach 1 MA. These results [4] also show that 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, low internal inductance $l_i \approx 0.35$ 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. The low density, which is below the 28 GHz ECH cut-off density, would allow the electron temperature of these plasmas to be increased by Electron Cyclotron Heating (ECH).

Strategy for Current Ramp-up of CHI Started Plasmas in NSTX-U: Plasma start-up methods currently envisioned for initial current generation in ST based reactors are anticipated to generate a

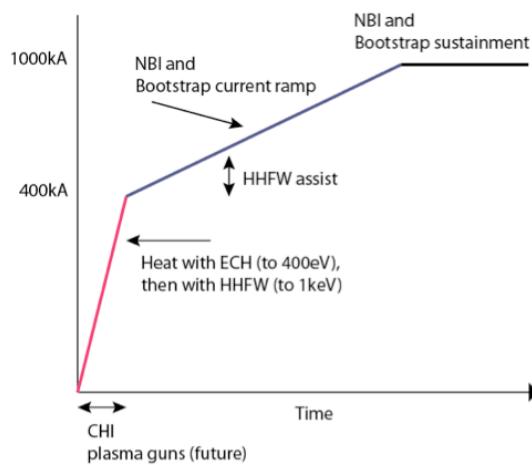


Fig. 1: NSTX-U current ramp-up scenario.

part of the total required current. This initial seed current needs to be ramped-up by other means to the levels required for sustained operation. Plasma start-up based on transient CHI is projected to generate about 400 kA of closed flux current in NSTX-U and about 20% of the full current in an FNSF based on an ST [6]. Thus, it is necessary that methods for non-inductive current ramp-up be demonstrated in present generation STs. This is an important NSTX-U program objective.

NSTX-U plans to develop this capability in a staged manner as qualitatively shown in Figure 1. The initial phase would generate closed flux plasma currents up to about the 400 kA level. Transient CHI

will be used as the front end of this scenario. Results from NSTX coupled with TSC simulations suggest that NSTX-U has considerably more injector flux capability than what is needed for generating 400 kA current using Transient CHI [4]. Results from NSTX have also shown that the average electron temperature of CHI plasmas is on the order of 20 to 30 eV. Although this temperature is expected to increase due to ohmic heating, at higher currents, it is very likely that some form of efficient electron heating system would be required to increase the temperature of these plasmas to a level where they could be coupled to neutral beams for current ramp-up without induction.

NSTX-U plans to use a 1 MW 28 GHz ECH system to boost the electron temperature of CHI started discharges to about 200-400 eV in about 20 ms. Simulations using the TSC code suggest that at 50% of the ITER L-mode confinement scaling, this temperature increase is possible. At the 300 eV electron temperatures, previous work on NSTX has shown that the electron temperature could be further increased to above 1 keV in 20 ms using less than 1 MW of High Harmonic Fast Wave (HHFW) power [7]. Discharges on NSTX have also demonstrated non-inductive current fractions of 0.7-1.1 in HHFW heated 300 kA plasmas [7]. At the higher toroidal field in NSTX-U (1 T vs. 0.55 T in NSTX), HHFW coupling to the plasma is anticipated to improve [7]. These aspects of the initial current start-up are shown labeled by the red line in Figure 1. TRANSP simulations show that the new second neutral beam set on NSTX-U could provide 3-4 times higher current drive at low plasma current [6]. This is due to a combination of 1.5 to 2 times higher current drive efficiency plus 2 times higher beam absorption. Initial TRANSP simulations for 300 kA plasmas suggest that the current drive efficiency at this lower current is also significant. The increased current drive requires the

electron temperature of these plasmas to be in the 800 eV range or higher. Neutral beam coupling to these targets should then be possible to allow the combination of NBI current drive and bootstrap current overdrive to ramp the current to the sustained operation levels.

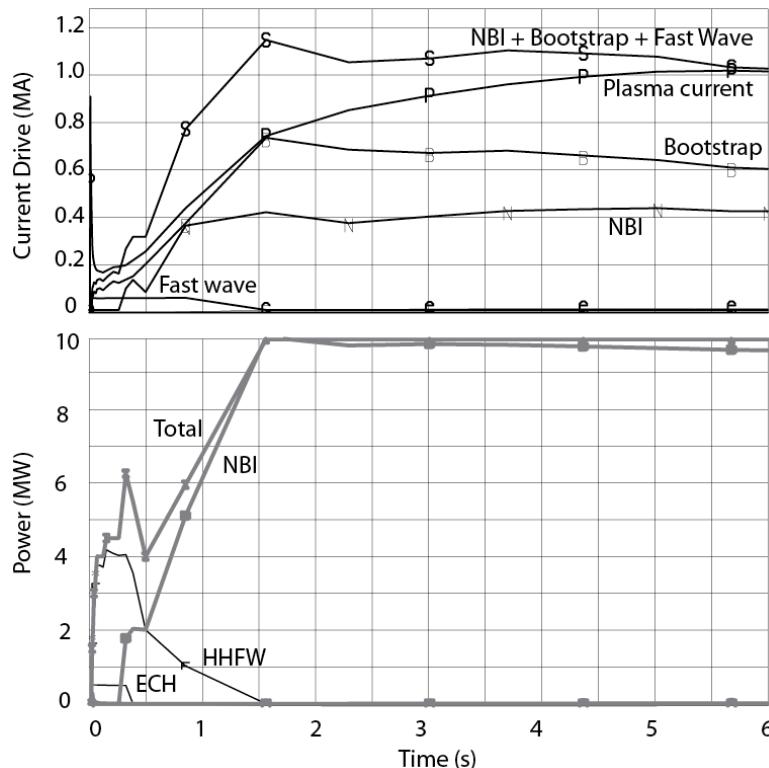


Fig. 2: Time traces from a TSC current ramp-up simulation. The top frame shows the different current drive components. The lower traces show the injected power traces.

Figure 2 – 3 show results from an initial full discharge scenario simulation that has all of the elements described above. The CHI discharge is initiated in TSC [8] as described in Reference [9], and a closed-flux target of >400 kA is established at 17 ms. This is the seed current that is subsequently ramped-up using HHFW and neutral beams. The discharge is initially heated using 0.5 MW of absorbed ECH

power. The HHFW power is ramped-up to 4 MW at 200 ms, maintained until 325 ms, then ramped down to zero. HHFW is assumed to generate 50 kA of fast wave current drive. Largely through a combination of bootstrap current drive the current decay of the CHI plasma is first slowed down, and then it begins to ramp-up. During this phase, the neutral beam power is increased in steps so that the combination of NBI CD and bootstrap current drive provide current overdrive and they ramp the plasma current to 1 MA at about 4.5s. As shown in Figure 3, throughout the discharge, the Greenwald density is maintained at about 0.5, the normalized internal plasma inductance below 0.7, the energy confinement time below 40 ms, the H-98 factor close to 1. For the Copi-Tang transport model used in this simulation the electron and ion temperatures are about 1.7 and 2.8 keV respectively.

Summary: 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. Some of the key results, not all of which are described in this paper are: (1) CHI current drive scales well as the machine size or toroidal field or both are increased, with projected start-up currents of about 20% of the sustained current in next-step STs and (2) The CHI generated plasmas on NSTX have desirable properties including low inductance and electron density and high elongation needed for subsequent non-inductive current ramp-up.

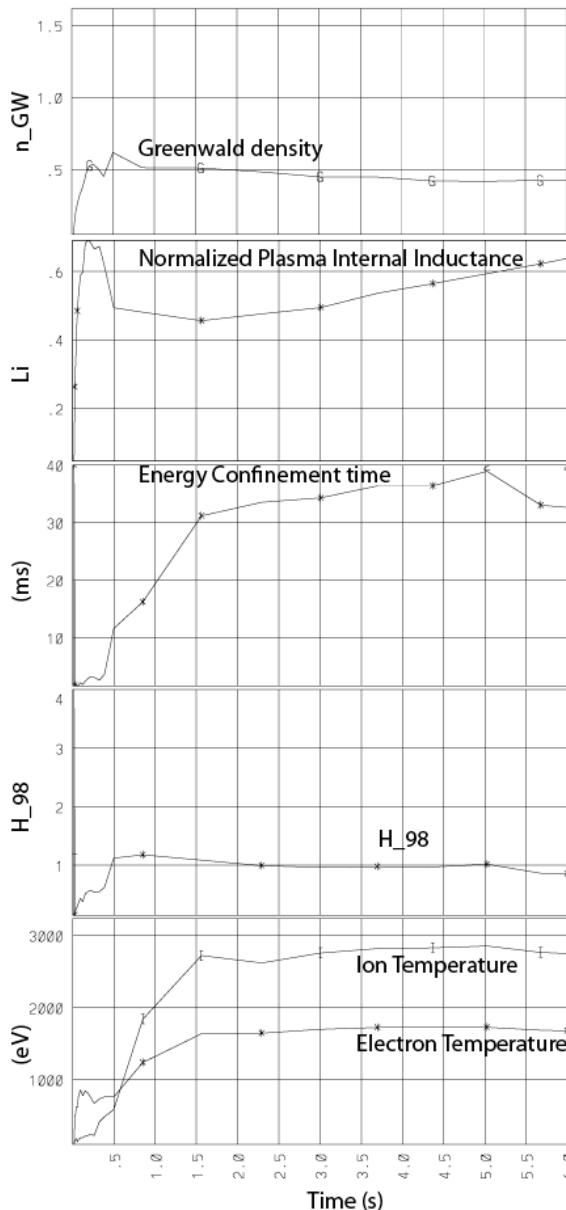


Fig. 3: Time traces showing plasma parameters for the simulation shown in Fig. 2.

Transient CHI plasma start-up on NSTX-U would benefit from numerous improvements including factor of two higher toroidal field, more than a factor of 2.5 higher injector flux than in NSTX, higher CHI operating voltage and capability for ECH heating.

Initial full discharge simulations with the TSC code, as well as previous experimental achievements on NSTX, suggest that with these new capabilities, NSTX-U is well equipped to study and develop full non-inductive current start-up and current ramp-up in support of an FNSF.

This work is supported by U.S. DOE Contracts DE-AC02-09CH11466, DE-FG02-99ER54519 AM08 and DE-SC0006757

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