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

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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 favorable scaling of the CHI start-up process with increasing machine size. These results from NSTX imply a current generation potential in excess of 500 kA in the NSTX-U currently under construction.

Both conventional aspect ratio tokamaks and spherical tokamaks (STs) have generally relied on a central solenoid to generate the initial plasma current and then to sustain that current against resistive dissipation. However, in a steady-state reactor, induction alone cannot be used for plasma current sustainment. The inclusion of a central solenoid in a tokamak to provide plasma startup limits the minimum aspect ratio and increases the device complexity. For reactors based on the ST concept, elimination of the central solenoid is essential, making alternate methods for plasma start-up necessary for such a reactor.

CHI [1] is implemented in NSTX by driving current from an external source along field lines that connect the inner and outer lower divertor plates. A CHI discharge is initiated by first energizing the toroidal field coils and the lower divertor coils to produce magnetic flux, known as the injector flux, linking the lower inner and outer divertor plates which are electrically isolated by a toroidal insulator in the vacuum vessel. After a programmed amount of gas is injected into the vacuum chamber, a 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.

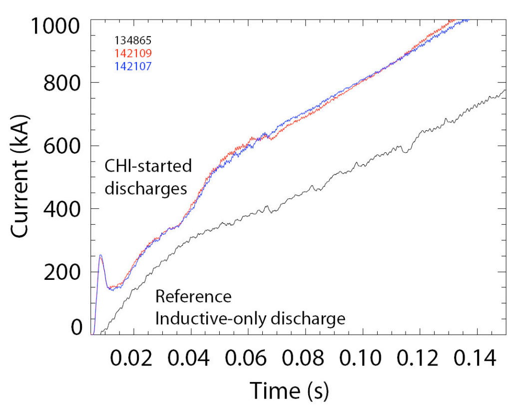

Fig. 1. Plasma current traces for discharges initiated with and without CHI.

Fig. 1 shows two CHI-started discharges that were then coupled to inductively driven ramp-up. The third discharge is an inductive-only case that is a non-CHI discharge from the NSTX database (assembled over 10 years of operation) that reached 1 MA in a shorter time than other L-mode discharges. For the CHI initiated discharge at 132 ms, a total of 258 mWb of central solenoid flux was required to ramp the discharge to 1 MA. The non-CHI discharges at this time only gets to about 0.7 MA and does not reach 1 MA until 160 ms, by which time 396 mWb of central solenoid flux had been consumed. Thus, the discharges assisted by CHI use only about 65% of the solenoid flux required for purely inductive startup of a 1MA L-mode discharge. To achieve these results it was essential to control the influx of low-Z impurities, mainly oxygen and carbon [2].

In Fig. 2, we show other parameters for discharges started with and without CHI. The CHI assisted discharges have much lower plasma internal inductance and their line-integral electron density is about one third that of the standard NSTX discharges. As a result of the lower inductance, the CHI started discharges also have a higher plasma elongation for a similar programming of the NSTX

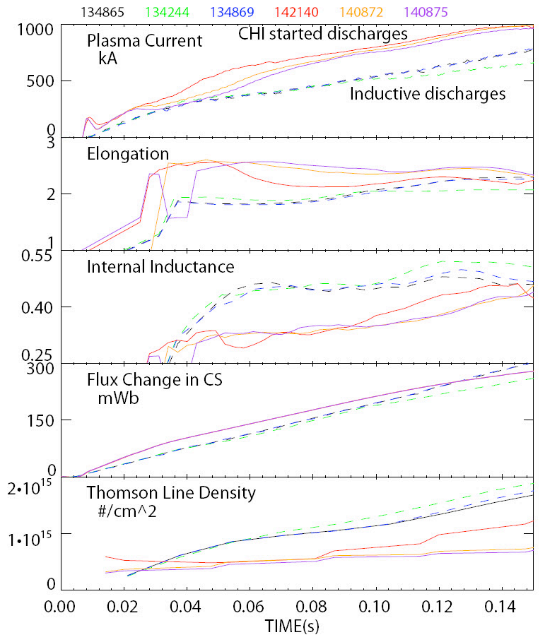

Fig. 2. Comparison of time traces for discharges with CHI start-up (shown in solid) and inductive-only startup (shown dashed)

shaping coils. Operational experience has shown that for the standard inductive startup in NSTX, both the higher plasma density and the slower current ramp rates of the discharges in Fig. 3 are required to avoid mhd instability during the current ramp. The lower internal inductance of CHI generated discharges is related to the hollow electron temperature profile, which is a characteristic of the CHI start-up process. This causes more of the current to flow in the outer region resulting in lower inductance plasma. This is advantageous for producing shaped equilibria 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 to provide an initial current profile similar to that which is achieved in conventional tokamaks through the use of high-power auxiliary heating, in conjunction with lower densities should benefit advanced scenario operations.

TSC is a time-dependent, free-boundary, predictive equilibrium and transport code [3] capable of simulating the evolution of the plasma, transport and discharge electromagnetics, including interaction with the plasma control system. It has now been used to simulate the evolution of transient CHI discharges in NSTX [4]. The results of a simulation for NSTX using 80% of the injector flux capability in NSTX are shown in Fig. 3. The modeled effect of applying 0.5MW of ECH power to raise the electron temperature by about 200eV and slow the resistive decay of the CHI initiated current is shown in panel (d). At this temperature, 2 MW of high-harmonic fast-wave heating power further could increase the electron temperature to over 600 eV.

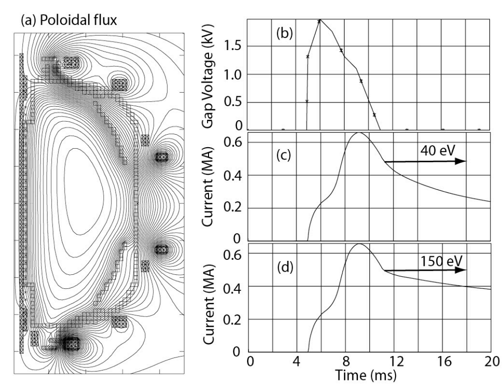

Fig. 3: TSC simulation of CHI start-up using 80% of the injector flux capability in NSTX. Show are (a) poloidal flux contours at time of peak current, (b) injector voltage, (c) plasma current for a discharge temperature of 40 eV and (d) plasma current for a discharge shown in (c) but with electron temperature increased to 150 eV at 11ms, such as could be expected with ECH heating.

The NSTX is now undergoing a major upgrade (NSTX-U) to increase the capabilities of its toroidal and poloidal field coils and to add a second 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 modeling projects that it should be possible to generate 500 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. The results from TSC simulations show that CHI could be an important tool for non-inductive start-up in next-step STs.

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