Demonstration of Tokamak Inductive Flux Saving by Transient Coaxial Helicity Injection on NSTX

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Discharges initiated by Transient Coaxial Helicity Injection (CHI) in NSTX have attained peak toroidal plasma currents up to 300 kA and when these discharges are coupled to induction from the central solenoid they develop up to 300 kA additional current compared to discharges initiated by induction only. In NSTX, reference inductive only discharges require 50% more solenoid flux than a CHI started discharge to reach 1 MA. These are the first discharges in NSTX that have generated 1 MA of plasma current using only 258 mWb of solenoid flux. In addition, the resulting discharge has low plasma density and normalized internal plasma inductance of 0.35 from the start of the discharge and through the inductive ramp, typical of the type of discharges required for advanced scenario operations. The Tokamak Simulation Code (TSC) has 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 and are consistent with the theoretical model for CHI plasma startup. Scaling based on the analysis of experimental results and TSC simulations indicates the possibility for substantial current generation potential by CHI in the upgrade to NSTX. These exciting new results from NSTX demonstrate that CHI is a viable solenoid-free plasma startup method for future STs and tokamaks.

I 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. In a steady-state reactor, a central solenoid cannot be used for plasma current sustainment. The inclusion of a central solenoid in a tokamak for plasma start-up limits the minimum aspect ratio and adds additional cost and complexity. For reactors based on the ST concept, elimination of the central solenoid is necessary. Thus alternate methods for plasma start-up are needed for such a reactor.

The generation of toroidal plasma current by Coaxial Helicity Injection (CHI) was originally developed for spheromak plasma formation [1] and has been used on several spheromak experiments including on the SSPX, CTX and RACE devices [2-4]. It has also been used in reconnection merging experiments [5,6] and for spherical torus plasma formation [7,8].

The first experiments utilizing CHI on NSTX used the method of *driven* or *steady-state* CHI for plasma current initiation [8]. However, the toroidal currents generated using this method could not be coupled to induction. Later, 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 ramped-up using induction [9]. The transient-CHI method has now been successfully used on NSTX for solenoid-free plasma start-up followed by inductive ramp-up [10]. These coupled discharges have now achieved toroidal currents >1 MA using significantly less inductive flux than standard inductive discharges in NSTX.

II Experimental Results

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 Reference [8-10]. The standard operating condition for CHI in NSTX uses the inner vessel and lower inner divertor plates as the cathode while the outer divertor plates and vessel are the anode. A CHI discharge is initiated by first energizing the toroidal field coils and the lower divertor coils to produce magnetic 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.

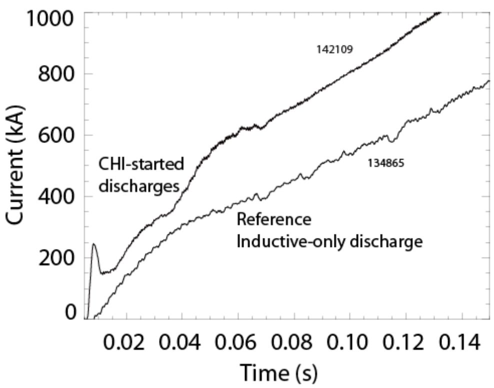

Figure 1: Shown are a CHI started discharge and a reference inductive-only discharge.

The results reported here were made possible by reductions to the low-Z impurities, mainly oxygen and carbon, as described in reference [10], and briefly summarized here. First, it was necessary to clean the lower divertor plates, which function as the CHI electrodes. This was accomplished by running several discharges at high injector current levels but with increased poloidal flux connecting the lower divertor plates (the injector flux) so that the discharge stayed connected to the lower divertor plates. Then, the lower divertor plates were coated with lithium by a pair of evaporator ovens mounted at the top of the vacuum chamber [11]. Third, 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 [10]. In the absence of this flux, once the CHI discharge contacted the upper divertor, a pronounced arc usually developed which generated low-Z impurities causing the CHI initiated discharge to become more resistive which rapidly consumed the poloidal flux generated in the plasma.

Fig. 1 shows a CHI started discharge that was coupled to induction. The second discharge is an inductive-only case 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 discharge 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 L-mode discharges from the NSTX data base require at least 50% more inductive flux than discharges assisted by CHI. The discharge on NSTX that consumed the least amount of solenoid flux to reach 1 MA transitioned to an H-mode. That discharge required 340 mWb to reach 1 MA, which is still significantly higher than the CHI started discharges [12]

These new results are described in greater detail in References [12,13], which 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, very low internal inductance $l_i \approx 0.3$ 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. Reference [12] also shows that CHI has tremendous plasma start-up potential in the Upgrade to NSTX due to improved injector coil design and higher toroidal field capability of 1T, consistent with earlier theoretical calculations [14].

III TSC Simulations

TSC is a time-dependent, free-boundary, predictive equilibrium and transport code [15-16]. It has the ability to aid in scenario development of both discharge energetics and plasma control systems. It solves fully dynamic MHD/Maxwell's equations coupled to transport and Ohms's law equations. It requires as input the device hardware and coil electrical characteristics, as well as assumptions concerning plasma density profile (or particle diffusivity), impurities, and other global discharge characteristics. 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 the fact that the poloidal flux and tangential electric field are 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. Open field lines are included, and the halo current is computed as part of the calculation. In this modeling, the NSTX vacuum vessel is modeled as a metallic structure with poloidal breaks at the top and bottom. An electric potential *V* is applied across the break.

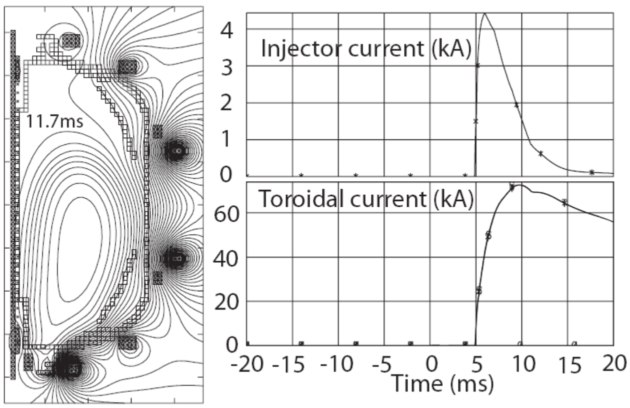

Figure 2: Shown are the poloidal flux contours, injector current and CHI produced toroidal current for NSTX discharge 118340 [Ref. 17].

The discharge being simulated is an early NSTX transient CHI discharge that successfully demonstrated current persistence, a condition when the CHI produced toroidal current persisted after the injector current had been reduced to zero. We used the same poloidal field (PF) coil currents as were used in NSTX Shot 118340. Due to the difficulty in computing the actual plasma resistance including the plasma-vessel sheath resistance in this case, we did not attempt to use the experimentally measured voltage, but rather applied a voltage *V* across the lower vessel gap and adjusted this value *V* to give approximate agreement with the measured toroidal current. In Fig. 2 we illustrate the results of the TSC calculations of the CHI experimental data shown in Fig. 2 in Reference [17]. The electron temperature in the simulations is maintained constant at 40 eV. About 60 kA of toroidal current is generated, and as in the experiment, the injector current is within a factor of two of the experimental value. The poloidal flux plots [18] show the plasma evolves in much the same way as observed experimentally from fast camera images of the plasma growth.

Generation of closed flux in TSC is as a result of an effective toroidal loop voltage induced by the CHI ejected poloidal flux that decreases as the injector current is reduced to zero. This is shown in Fig. 2 of Reference [18], which is a plot of the induced loop voltage at Z = -0.3 m along the inner wall of NSTX. It shows the induction of large negative loop voltage as the plasma grows. The rapid injection of poloidal flux is responsible for the induced negative loop voltage. However, as the plasma current begins to decay as a result of the pre-programmed injector voltage being reduced to zero, a relatively smaller positive loop voltage is induced, and coincident with this, closed flux surfaces are generated in the discharge.

Reference [18] provides additional details including showing consistency with earlier theoretical predictions [14]. It also shows that CHI scaling with toroidal field is favorable for larger machines and that with acceptable amounts of injector current, plasma currents on the order 600 kA could be generated in the present NSTX if the toroidal field is increased to 1T.

IV Summary

Significant improvements to CHI performance in NSTX were achieved by reducing low-Z impurity influx into the plasma discharge and by applying additional "buffer" flux with a pair of absorber poloidal field coils to suppress absorber arcs. As a result, 300 kA of start-up current has been produced using just 29 kJ of stored capacitor bank energy. When these CHI started discharges are ramped up using induction, it is found that they require about 40% less inductive flux from the solenoid to reach 1 MA plasma current than inductive-only discharges. Furthermore, the resulting CHI started discharge has lower plasma density and normalized internal plasma inductance throughout the inductive ramp.

Simulations with the TSC code have been found to be consistent with the theoretical model for CHI plasma startup. These simulations now provide a new and powerful capability for optimizing and designing CHI systems in future upgrades to NSTX. Results show that for a given injector current, closed flux generation using Transient CHI scales with increased toroidal flux in the vessel. This is a parameter that is expected to increase in future STs that are expected to have higher toroidal field and a larger plasma cross-section. As a result of higher current multiplication, the required injector current decreases. This is an important result as reduced injector current translates to a more efficient system and also to reduced interactions with the electrodes.

Scaling to NSTX-U shows that CHI has the potential to generate a significant portion of the current needed for subsequent non-inductive current ramp-up and sustainment by the bootstrap effect and neutral beam driven current. These new results from NSTX demonstrate that CHI is a viable solenoid-free plasma startup method for advanced scenarios in future STs.

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