Solenoid-free Plasma Start-up Using Transient CHI in NSTX-U

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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 [1,2]. In addition, the CHI-initiated discharges have lower density and a low normalized internal plasma inductance of 0.35, desired for achieving advanced scenarios in NSTX-U. CHI is incorporated into the NSTX-U machine design, to be used for the start-up phase of a full non-solenoidal plasma ramp-up scenario. The objective for first two years of CHI research on NSTX-U is to re-establish transient CHI start-up in the new vessel geometry, and to generate 400 kA of closed-flux start-up current. In support of these planned experiments, the TSC code [S.C. Jardin, et al., J. Comput. Phys. **66**, 481 (1986)] has been used to develop transient CHI start-up scenarios using the full NSTX-U TSC vessel geometry, implemented during the past year. We have also used the resistive MHD code NIMROD, to understand the mechanisms that lead to the generation of closed flux plasma in a transient CHI discharge [3]. These simulations show that the new machine capabilities on NSTX-U significantly enhance CHI-startup capability.

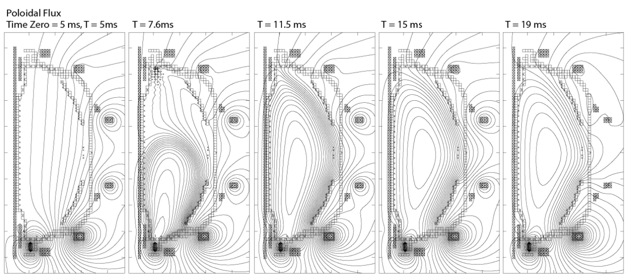

Figure 1: Evolution of the injector flux in a transient CHI discharge initiation in the NSTX-U vessel geometry.

Tokamaks have generally relied on a central solenoid to generate the initial plasma current. However, in a steady-state reactor, induction alone cannot be used for plasma current sustainment. The inclusion of a solenoid for start-up limits the minimum aspect ratio and increases the device complexity.

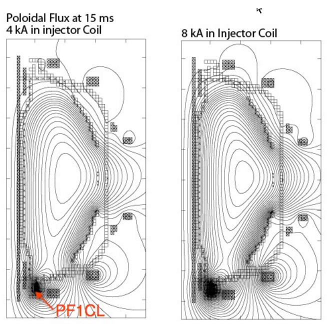

Figure 2: Flux surface plots at 15 ms for PF1C coil currents of 4 and 8 kA.

CHI [T.R. Jarboe, Fusion Technol. **15** 7 (1989)] is implemented in NSTX-U by driving current from an external source along field lines that connect the inner and outer lower divertor plates. The generation of closed flux in TSC simulations [4] is the result of an effective (positive) toroidal loop voltage induced by the decaying poloidal flux on the open field lines as the injector current is rapidly reduced in magnitude. Figure 1, which is a TSC simulation in the NSTX-U vessel geometry, shows the evolution of the injected flux starting from t = 5 ms, at which time the discharge is initiated. For these cases a 5 ms voltage pulse is applied across the divertor plates, and of sufficient magnitude to allow the discharge the fill the vessel. A relatively low and constant in time current of 2 kA is used in the primary CHI injector coil (the PF1CL coil). Relatively smaller levels of currents are used in the other nearby coils. This is typical of the initial transient CHI-started discharges planned for NSTX-U. Figure 2 shows the effect of increasing the current in the primary injector coil to 4 kA and 8 kA. The injector flux generated by this coil is directly proportional to the magnitude of the current driven in this coil. At the 16 kA maximum current rating, the PF1CL coil is capable of generating 250 mWb of injector flux.

The corresponding CHI-generated toroidal current for these three cases is 150 kA, 300 kA and about 700 kA respectively, roughly reflecting the increased poloidal flux injection as the current in the injector coil is increased. Analysis of experimental results from NSTX shows that a very large fraction of the injected flux (~80%) is retained as closed flux [1]. NSTX CHI discharges that generated 200 kA of closed flux current required 50 mWb of injector poloidal flux [1], which along with these TSC simulations suggests that NSTX-U should be capable of generating significantly more than the 400 kA closed flux current believed to be necessary for full non-inductive start-up and ramp-up.

The higher current generation potential in NSTX-U is due to several new hardware improvements. These are: 1) factor of two increase in the toroidal field, which allows twice as much injector flux to be injected at the same level of injector current, 2) factor of 3-4 increase in the all-important injector flux itself, 3) improved positioning of the divertor coils that allows a narrow flux foot print to be more easily generated, 4) higher CHI operating voltage, 5) considerably improved Li coating capabilities to reduce low-Z impurities and 6) a planned 1 MW, 28 GHz ECH heating system, to increase the T_e of CHI-produced discharges.

The 3-D resistive MHD code NIMROD, is especially well suited for studying the early dynamic phase of a transient CHI discharge. As part of an effort to develop a full NIMROD model of transient CHI start-up, we have used NIMROD to understand the importance of many of the NSTX-U machine enhancing parameters and their role in improving the performance of transient CHI discharges. The very first simulations with NIMROD showed that the magnetic Lundquist number must be above a threshold value, corresponding to electron temperatures on the order of about 12 eV or higher, before closed flux surfaces can form [3]. Under this condition, it was found that as the injector voltage (and current) is rapidly reduced, a toroidal electric field is generated in the injector region that through the action of the $E_{toroidal} \times B_{poloidal}$ drift causes oppositely directed field lines to come together and reconnect before being dissipated due to high resistivity. Simulations have also confirmed the role of the magnitude of the injector flux, the importance of a narrow flux foot print width, and rapid time scales required for reducing the injector voltage and (current) in increasing the magnitude of the closed flux fraction [F. Ebrahimi, et al., submitted to Phys. Plasmas]. What is particularly noteworthy is that these simulations suggest that the reconnection mechanisms for transient CHI appear to be very similar to 2-D Sweet-Parker type reconnection, and 3-D effects do not seem to be important. The characteristics of an elongated current sheet, typical of Sweet-Parker reconnection are shown in Figure 3 [3].

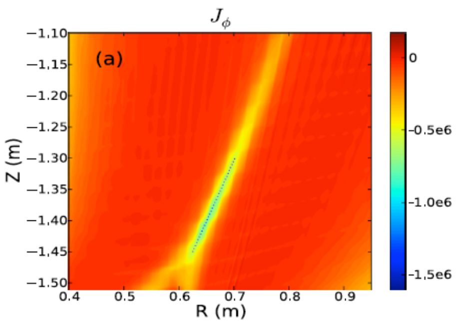

Figure 3: Nimrod simulation shows an elongated reconnection current sheet near the injector region.

The NSTX is now nearing completion of a major upgrade (NSTX-U) to increase the capabilities of its toroidal and poloidal field coils. Analysis of the NSTX results and numerical simulations shows that the amount of closed-flux current generated by CHI is closely related to the initially applied injector flux [1,3,4]. 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 well over the required 400 kA of closed-flux current with CHI in NSTX-U. This work was supported by U.S. DOE contracts DE-FG02-99ER54519, DOE-FG02-12ER55115, and DE-AC02-09CH11466.

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