Transient CHI Plasma Start-up Simulations and Projections to NSTX-U

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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. 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 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 3-D resistive MHD code NIMROD, to understand the mechanisms that lead to the generation of closed flux plasma in a transient CHI discharge.

1. Introduction

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. NSTX, and the soon to become operational NSTX-U device [1], at PPPL, will use Transient Coaxial Helicity Injection (CHI) to achieve solenoid-free plasma start-up [2]. The method of CHI relies on electrostatic helicity injection for initiating the plasma discharge [3]. CHI is implemented in NSTX and NSTX-U by driving current from an external source along open field lines that connect the inner and outer lower divertor plates [2], which are electrically separated from each other by toroidal insulators located at the top and bottom of the vessel, as shown in Figure 1. CHI can be applied using two methods. In the first approach, known as *driven* CHI or *steady-state* CHI, the power supply current driven on open field lines, known as the injector current, is continuously driven. One then relies on non-axisymmetric magnetic activity to drive current on closed field lines [4]. While this method offers the potential for steady-state current drive, and was initially tested on NSTX [5] it was found that discharges generated using this approach could not be successfully coupled to subsequent inductive drive, because of an influx of low-Z impurities. The method is being further developed on smaller machines; including novel approaches that drive steady-state current using a method that relies on steady-state inductive drive [6]. In the second approach, known as *transient* CHI, the current on the open-field lines is rapidly reduced on the time scales it takes for the open-field line plasma discharge to fill the vessel. If the open-field line injector flux footprints are narrow, then in a process of nearly axisymmetric reconnection near the injector region, the injected poloidal flux reconnects generating high-quality closed flux equilibrium. The method was first developed on the HIT-II device at the University of

Washington [7] and later successfully applied to the much larger (30 times in plasma volume) NSTX device at PPPL.

NSTX-U is designed with a major/minor radius of 0.93/0.55 m and a toroidal field at the nominal major radius of up to 1 T (0.55 T on NSTX). It will be equipped with a central solenoid providing up to 2.10 Wb (0.75 Wb on NSTX) of inductive flux (double swung), which can generate plasma currents up to 2 MA [8]. The outer poloidal field coils are identical to the ones used on NSTX and will be located about 0.5 m away from the plasma boundary. The plasma-facing boundary, as on NSTX, will initially be composed of graphite tiles. Starting from 2017, in a staged approach, NSTX-U will undergo an upgrade during which many of the graphite tiles would be replaced with metallic tiles. NSTX-U would rely largely on lithium coatings of the plasma facing surfaces to reduce the influx of low-Z impurities and to reduce wall recycling. The lithium coating systems on NSTX-U would expand on the capabilities available on NSTX, by allowing full coverage of both the lower and upper divertor tiles. NSTX-U will also be equipped with a second tangential neutral beam system, which is well aligned to drive current [1]. Much of the NSTX-U plan for full non-inductive start-up, in which CHI will be used as the front end, for subsequent non-inductive current ramp-up to the steady-state current sustainment levels will rely extensively on the new second neutral beam system capability.

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 [9] 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 3-D resistive MHD code NIMROD, to understand the mechanisms that lead to the generation of closed flux plasma.

2. Scaling relations for Transient CHI Start-up discharges

The maximum toroidal current that can be generated by CHI is given by the relation [3]:

$$I_{tor} = I_{inj}\ (\phi_{tor}/\psi_{inj}) \quad (1)$$

Here I_{tor} is the toroidal current generated by CHI, I_{inj} is the injector current, which is the same as the current supplied by the capacitor bank power supply, ϕ_{tor} is the toroidal flux contained within the CHI plasma discharge and ψ_{inj} is the injector poloidal flux. As described in Figure 1, the injector flux is generated by driving current in a lower divertor coil. In CHI terminology, this coil is referred to as the CHI injector flux coil. This flux connects the inner and outer divertor plates. The magnitude of the injector flux can be increased by increasing the current driven in the injector coil.

The maximum toroidal current generated by CHI is given as the product of the maximum current multiplication ratio (ϕ_{tor}/ψ_{inj}) and the externally driven injector current. The current multiplication factor is the ratio of the toroidal current to the injector current. It is important to note that the injector current cannot be arbitrarily increased to attain a higher toroidal current. The injector current is clamped at or near what is known as the bubble burst current limit. This is the minimum magnitude of the capacitor bank provided current required for injecting the injector flux that initially connects the lower divertor plates into the vessel. It is given by the relation [3]:

$$I_{inj} = 2(\psi_{inj}/\mu_0 d)^2/I_{TF} \quad (2)$$

As shown in Figure 1, d is the width of the injector flux footprint on the electrodes and I_{TF} is the current through the centre leg of the toroidal field coil.

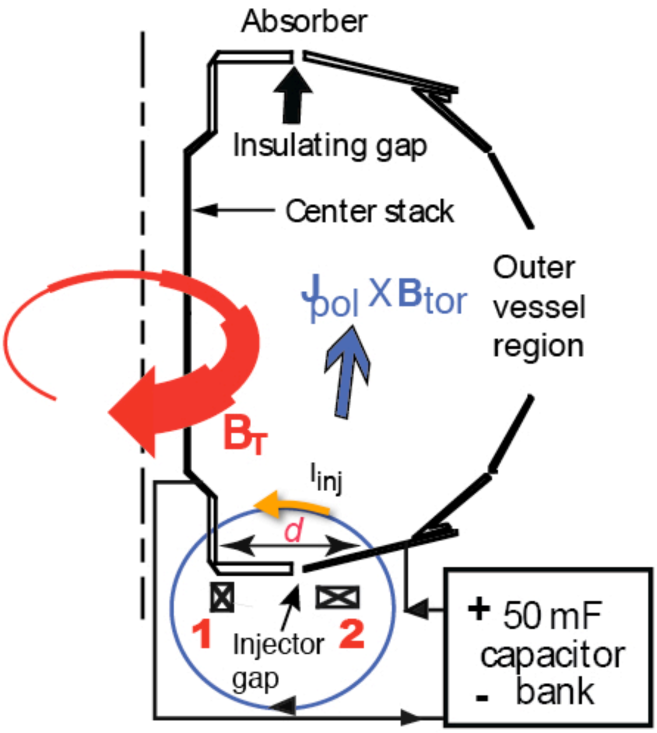

FIG 1. Cartoon showing CHI start-up in NSTX and NSTX-U. The coil labelled 1 is the equivalent of the injector flux coil, which generates the injector flux connecting the outer and inner divertor plates, which are electrically separated.

By inserting the expression for the injector current (Eqn. 2) into the expression for the total toroidal current (Eqn. 1), and recognizing that the toroidal flux ϕ_{tor} is directly proportional to I_{TF}, it can be seen that the maximum toroidal current is linearly proportional to the injector flux. These scalings have been experimentally verified on the HIT-II device [4].

The increased toroidal flux is, however, extremely important because it decreases the amount of injector current corresponding to any particular values of toroidal current and injector flux. Reducing the amount of injector current is quite important for any DC helicity injection technique, as it reduces the current density on the electrode surfaces, thereby reducing the incidence of sputtering at the electrode, and producing a cleaner discharge. This is the primary reason why a device such as NSTX is able to generate 200 kA of closed flux current using a few kA of injector current, and have current multiplication factors as large as 60, whereas, spheromaks, in the absence of significant dynamo current drive, typically have current multiplication factors of 4 or less and would therefore require about 50 kA of injector current to generate the same level of toroidal current.

Thus the maximum closed flux current that can be generated by a transient CHI discharge is primarily determined by the amount of poloidal flux that can be injected into the vessel. In the absence of any dynamo activity, it is this flux that eventually reconnects at the injector region to generate a closed flux configuration. The scaling of injected poloidal flux with the CHI generated toroidal current is also seen in simulations using the TSC and NIMROD codes [10,11,12]. In NSTX transient CHI discharges, a large fraction of this injected flux is retained as closed poloidal flux in the resulting discharge [13]. Thus far on NSTX, 50 mWb of poloidal flux has been injected, resulting in closed flux plasma currents of about 200 kA. On the NSTX-U device, to begin operation early in 2015, the capability of the injector flux coil has been increased so that considerably more than 200 mWb of poloidal flux could be injected, which is expected to significantly increase the start-up current magnitude in NSTX-U.

2.1. TSC simulations

In preparation for transient CHI experiments on NSTX-U we have developed a model using the Tokamak Simulation Code (TSC) [9] that uses the NSTX-U vessel geometry. TSC is a time-dependent, free-boundary, predictive equilibrium and transport code. 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.

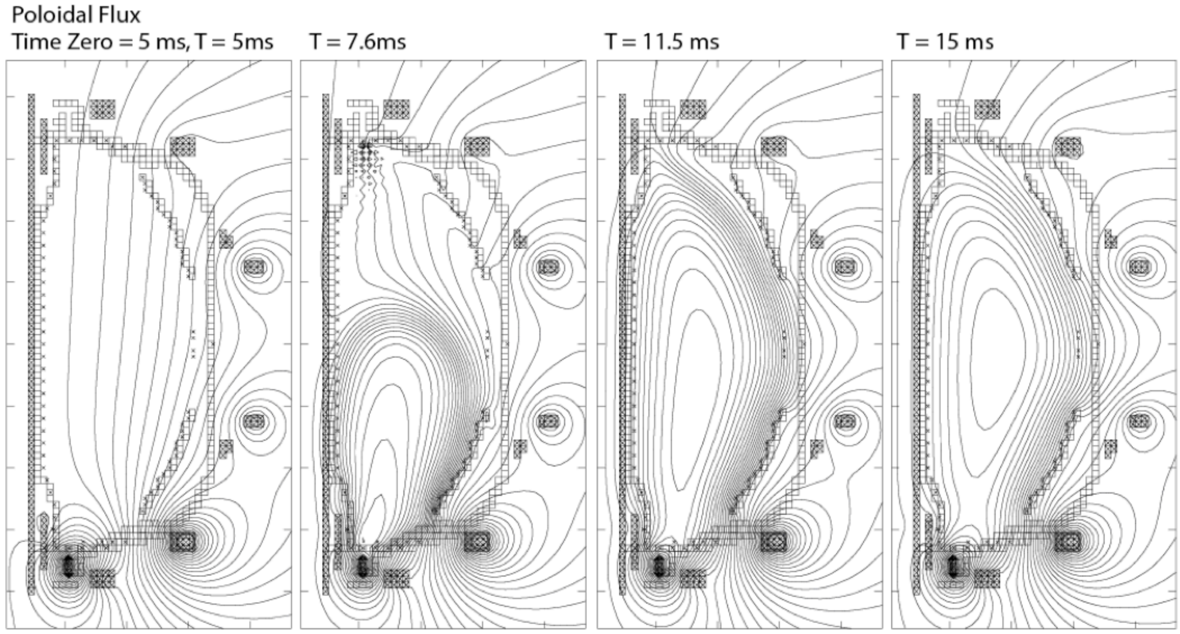

FIG 2. Evolution of the injector flux in a TSC simulated transient CHI discharge in the NSTX-U vessel geometry. The current in the injector coil is 40 kA.turns.

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 transient CHI discharge initiation, it is the injector current and injector flux that are the governing parameters, we adopted the modelling strategy of adjusting injector voltage in order to match the measured current rather than simply applying the measured injector voltage. This approach is adequate because this is also what is done experimentally. On the same machine, as the divertor surface conditions change, either due to increased gas loading on the electrodes or due to increased surface impurities, the voltage is adjusted to obtain the required injector current. Note that in the equation for the bubble burst current (Eqn. 2), the injector current and not the voltage is the governing parameter for overcoming the magnetic field line tension of the injector flux.

TSC simulations have been previously used to simulate transient CHI discharges from NSTX [10]. The generation of closed flux in TSC simulations 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 rapidly reduced in magnitude. Reference [10] provides additional details showing consistency with earlier theoretical predictions [3]. 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 injector flux capability in NSTX-U. The higher toroidal field in NSTX-U allows more poloidal flux to be injected at the same level of injector current, as also described by Eqn. 2.

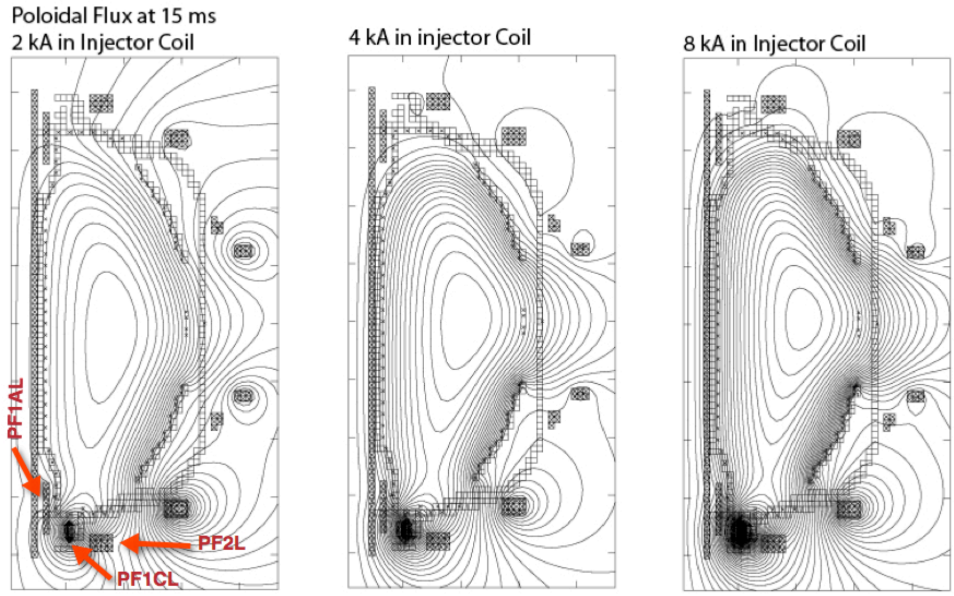

FIG 3. Flux surface plots at t = 15ms, for variations in the injector coil current. The injector coil has 20 turns.

These studies in the new NSTX-U vessel geometry, examines the evolution of the injected poloidal flux as the magnitude of the injector flux is changed. The model has also been simplified by using constant in time coil currents but thus far no optimizations have been conducted, such as for example using the appropriate vertical field magnitude and shaping required for the current in the CHI-produced plasma discharge or the appropriate voltage magnitude and pulse.

Figure 2, 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 (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 3 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 [13]. NSTX CHI discharges that generated 200 kA of closed flux current required 50 mWb of injector poloidal flux [13], 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 current ramp-up [14].

2.2. NIMROD simulations

The 3-D Resistive MHD code, NIMROD [15], is especially well suited for studying the early dynamic phase of a transient CHI discharge. During the past two years, it has been used to model transient CHI start-up in NSTX; to improve understanding of the physics of injection, flux-surface closure, and current drive for CHI plasmas; and to extend these results to NSTX-U. A simplified model is used to understand the basic physics of CHI plasma formation. These simulations use constant in time coil currents throughout the discharge. Thus no effort is made to adjust the magnitude of the vertical field as the plasma current increases.

Axisymmetric (n = 0) simulations with a poloidal grid of 45 × 90 fourth or fifth order finite elements are performed in the NSTX vessel geometry [16,17]. The initial injector flux is generated by driving current in the NSTX divertor and poloidal field coil [12], which are kept fixed in time (with fixed boundary field). A uniform voltage is applied across the injector gap at t = 6ms and turned off at 9 ms. The voltage at the opposite end of the vessel (in the upper divertor plate region), in the simulations, is determined by requiring the total toroidal flux to be constant in time inside the vessel. The normal flows at the injector and absorber gap are E × B flows. Zero pressure simulations are performed, where temperature and number density are not evolved. To facilitate comparison with experimental conditions, for each simulation at uniform magnetic diffusivity (resistivity), constant temperature values are specified. A uniform number density of 4×10^{18} m^3 for deuterium plasma is used. We have also performed simulations including non-axisymmetric n = 1 mode in both zero pressure and finite pressure cases, and no significant effect was found [12].

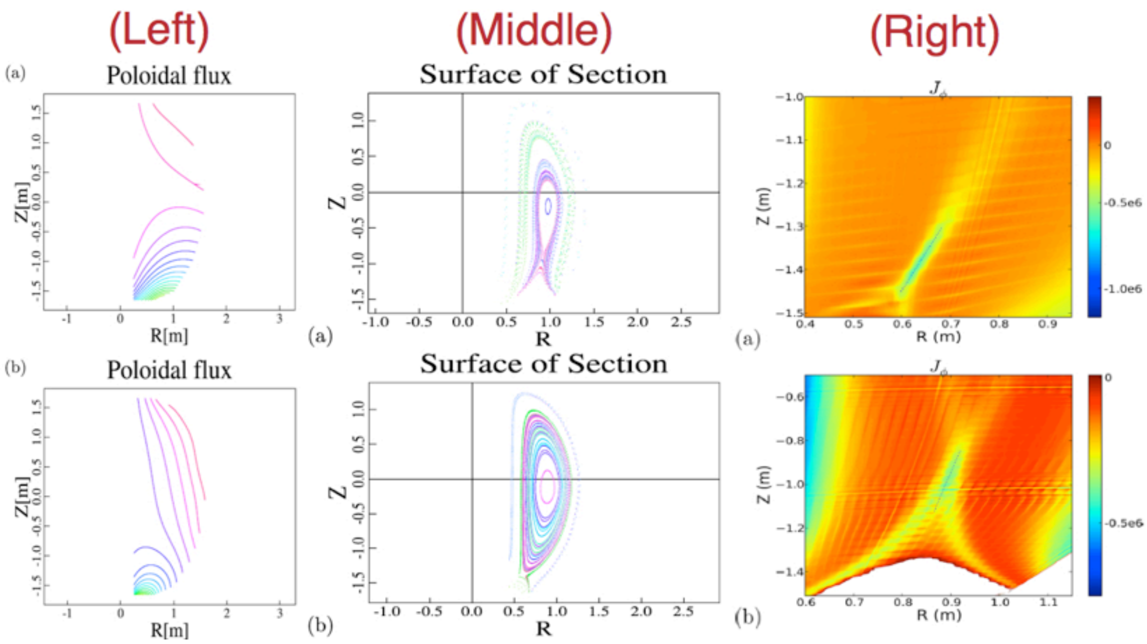

FIG 4. (Left) Initial poloidal fluxes for (a) wide footprint, and (b) narrow footprint. (Middle) Poincare plots for the two cases after CHI plasma formation. The much more pronounced closed flux formation for the narrow flux foot print case (b) is clearly seen. (Right) Localized current sheet formation during reconnection (a) narrow and (b) wide footprint cases.

The very first simulations 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 [17]. It was found that, with large magnetic diffusivity ($\eta\sim$ 400 m^2/s) (equivalent to T_e = 1eV) there was no flux closure. A small volume of closed flux forms at magnetic diffusivities of about ($\eta \sim 40 - 20\ m^2/s$). The volume of closed flux surfaces increases as the magnetic diffusivity is reduced to ($\eta \sim 8\ m^2/s$) (equivalent to $T_e = 14$ eV).

It was also found that, as the injector voltage is turned off and the evolving toroidal magnetic field decreases in the injector region, the compression from the toroidal magnetic field exerts an effective bidirectional pinch force that brings the oppositely directed fields together to reconnect. Consistent with the bidirectional pinch force, as the injector voltage is turned off, a radial pinch $E \times B$ flow is generated, where the electric field (loop voltage) in the toroidal direction induces the poloidal-field evolution that leads to reconnection [17].

An important result is the observation that closed flux surfaces during transient CHI can be explained through 2-D Sweet-Parker type reconnection, and 3-D non-axisymmetric modes do not appear to play a dominant role [17]. There are similarities between the transient Sweet-Parker reconnection found here and that reported in forced-reconnection laboratory plasmas [18]. The characteristics of an elongated current sheet, typical of Sweet-Parker reconnection are shown in Figure 4.

Recent simulations have 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 [12]. With increasing injector flux the amount of closed flux proportionally increases, consistent with earlier TSC simulations [10] and Zero-D models [3] that indicated that this should indeed be the case for transient CHI discharges. The closed flux fraction also increases with the rapidity with which the injector voltage and current are reduced, and consistent with earlier understanding that this is an important operational requirement for transient CHI.

Experimentally it is known that the CHI injector flux footprint width must be narrow for increasing the magnitude of the closed flux fraction. This is also seen in these recent simulations and is shown in Figure 4. Figure 4 (Left) shows the case of the wide and narrow footprint cases. The ratio of the closed current to the total plasma current is only 1.8% for the wide foot print case, but increases to >12% for the narrow footprint case (Figure 4 - Middle). In these simulations, the current sheet and X-point are formed at different locations. For the wide footprint case, the current sheet and X point are formed far from the injector gap. For the narrow footprint case, it forms near the injector gap (Figure 4 – Right). The plasma outflows in the narrow footprint case reach velocities up to 8500 m/s, much stronger than for the wide footprint case.

3. Summary and Conclusions

The physics insights gained from these simulations are as follows. TSC simulations show that closed flux surfaces begin to form soon after a positive toroidal loop voltage is generated. Physically, this loop voltage is generated due to the decaying poloidal flux on open field lines, and is analogous to the large loop voltage that is predicted to form in ITER immediately following a thermal quench, as the poloidal flux in ITER begins to decay. NIMROD results also show the formation of a toroidal electric field in the injector region. The NIMROD simulations offer greater insight by showing that this electric field acts on the poloidal injector flux and brings oppositely directed field lines closer together and allow them to reconnect, forming closed flux surfaces. NIMROD simulations provide a more complete picture of magnetic reconnection processes during transient CHI. Both ideal Alfvenic and resistive time scales are resolved in NIMROD. Local and global characteristics of magnetic reconnection, including flows and current sheet formation, are elucidated. The greater the amount of injected poloidal flux, more field lines reconnect and the closed flux magnitude increases. The closer the oppositely directed field lines are in the injector region, less time is required for them to come together. Both of which are desirable for increasing the closed flux fraction. Finally, they show that T_e must be above some threshold value, suggesting that at too low a value of T_e any closed flux plasma that may have formed would decay at a rate faster than it is being formed.

These simulation results give confidence that the current generation potential in NSTX-U is indeed significantly enhanced 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 needed for injecting more flux, 5) improved Li coating capabilities to reduce low-Z impurities needed for increasing T_e, and 6) a planned 1 MW, 28 GHz ECH system, to increase T_e of CHI-produced discharges. 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. 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 is supported by U.S. DOE contracts DE-FG02-99ER54519, DOE-FG02-12ER55115, and DE-AC02-09CH11466.

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