Design Details of the Transient CHI Plasma Start-up System on NSTX-U

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***Abstract*— Elimination of the central solenoid would simplify the engineering design of a fusion nuclear science facility and tokamak based devices. The method of transient coaxial helicity injection (CHI) has successfully demonstrated formation of a high-quality closed flux plasma in NSTX and will be used as the front end of the start-up method for a full demonstration of noninductive current start-up, followed by noninductive current ramp-up using neutral beams in the NSTX-U device that is now under construction at the Princeton Plasma Physics Laboratory. CHI is implemented by driving current along open field lines that connect the lower inner and outer divertor plates of a spherical torus. The engineering system requirements and the design of the CHI system on NSTX-U are described.**

***Index Terms*— CHI, helicity injection, noninductive, NSTX, NSTX-U, plasma start-up, solenoid-free, spherical torus (ST).**

I. Introduction

THE need for solenoid-free current start-up is essential to the viability of the spherical torus concept, and advanced tokamak designs eliminate the central solenoid to improve reactor performance [1]. The method of coaxial helicity injection (CHI) relies on electrostatic helicity injection for initiating the plasma discharge [2]. The method has previously been used in spheromak research [3]. A CHI discharge is initiated by driving current along open field lines that connect the lower inner and outer divertor plates, which are electrically separated from each other. 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 nonaxisymmetric 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 a 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 Princeton Plasma Physics Laboratory (PPPL) [8].

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II. Implementation of CHI on NSTX-U

A. NSTX-U Device

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. 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 entire 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 that is well aligned to drive current. Much of the NSTX-U plan for full noninductive start-up, in which CHI will be used as the front end, for subsequent noninductive current ramp-up to the steady-state current sustainment levels will rely extensively on the new second neutral beam system capability.

B. CHI Plasma Start-Up on NSTX-U

As shown in Fig. 1, CHI will be implemented on NSTX-U by injecting current through the plasma, on open field lines, using an external capacitor bank based power supply. These field lines, known as the injector flux, are generated using the lower divertor coils. On NSTX-U, the primary injector coil

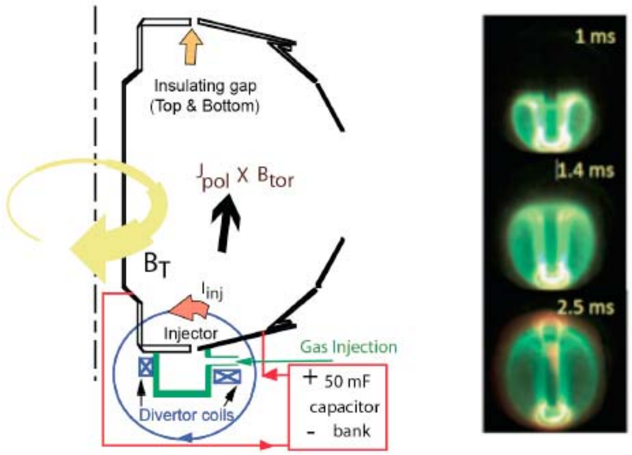

Fig. 1. Cartoon showing components required for CHI discharge initiation in NSTX-U, and fish eye camera images of an evolving CHI discharge in NSTX.

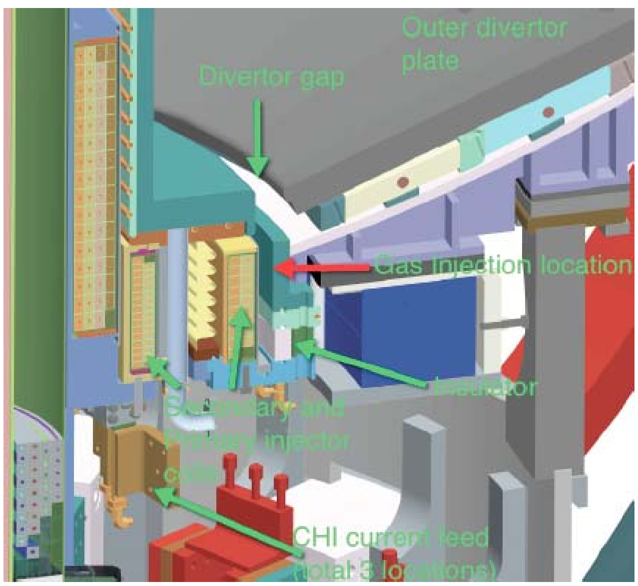

Fig. 2. 3-D drawing of the lower divertor region of NSTX-U showing the secondary and primary injector flux coils, the gas injection location, and the CHI insulator.

that is closer to the divertor gap (Fig. 2), would provide most of the injector flux, and initial start-up scenarios would rely only on this coil for generating the injector flux. The magnetic flux generated by this coil would connect the lower inner and outer divertor plates that are electrically separated by the injector gap, as shown in Figs. 1 and 2. Electrical separation of the inner and outer vessel components is achieved using two toroidal ceramic insulators, one at the bottom (Fig. 2) and an identical one at the top of the machine. About 1 to 3 torr·L of deuterium gas would be injected in the region below the divertor plates, at the location marked in Fig. 2, and a 2 kV capacitor bank (20–50 mF) would be discharged across the lower divertor plates.

The high-voltage electrical discharge would initiate a plasma discharge on the open-field lines. Because of the presence of a strong toroidal field, the driven current develops a strong toroidal component. This is the initial process of toroidal current generation. If the driven current magnitude is increased, so that the $J_{\mathrm{pol}} \times B_{\mathbf{toroidal}}$ force exceeds the magnetic field line tension of the injector poloidal flux [2], then the injected poloidal flux will extend into the NSTX-U vessel, as shown by the fast camera images for a discharge evolution in NSTX. The plasma would grow quickly, in about 2–5 ms, to fill the vessel. For transient CHI, on this time scale, the injector current is rapidly reduced. Through the choice of an appropriately sized capacitor bank much of this happens naturally as the stored energy in the capacitor bank is depleted. This process is sometimes assisted through the use of a fast crowbar system that is described later.

In addition to this, other poloidal field coils in the divertor region are driven in a polarity opposite to that used for the primary injector coil to reduce the flux foot print width on the lower divertor plates. This narrow flux foot print facilitates magnetic reconnection, which causes the injected poloidal flux to remain in the vessel as a closed flux plasma configuration after the field lines reconnect near the injector region.

The generated closed flux plasma on NSTX carried over 200 kA of current, and this value is projected to increase to over 400 kA in NSTX-U due to the much higher magnitude of the available injector flux and capacitor bank system capability. The subsequent noninductive current ramp-up scenarios on NSTX-U would use this initial target for a demonstration of noninductive current ramp-up and sustainment.

III. Improvements to CHI Systems on NSTX-U

NSTX-U will have numerous upgrades that benefit CHI research. These are briefly described below.

The magnitude of plasma current that can be generated using transient CHI is directly proportional to the amount of open poloidal flux injected by the CHI discharge into the vessel. This is because, in the absence of dynamo current drive mechanisms, all the poloidal flux, the eventual closed flux plasma equilibrium contains must come from the poloidal magnetic flux injected by the CHI discharge. These are described in more detail in [9], and simulations with the tokamak simulation code (TSC) also demonstrate this scaling.

NSTX-U has two injector flux coils. The primary coil (Fig. 2) and in Fig. 3, is much closer to the divertor gap than the corresponding coil in NSTX. This is numerically shown in Table I, that lists the parameters for the primary poloidal coils that are necessary to generate a CHI discharge. As a result the poloidal flux generated by this coil much more efficiently connects the inner and outer divertor plates. As a result, the injector poloidal flux capability increases from 80 mWb in NSTX to 250 mWb in NSTX-U using the primary PF1CL coil and to 350 mWb if the secondary PF1BL coil is also used. The corresponding poloidal flux in a 400 kA closed flux equilibrium at a normalized plasma internal inductance of 0.35 is 82 mWb, which suggests that transient CHI on NSTX-U has the potential to generate considerably more than the 400 kA that is necessary for coupling to neutral beams for subsequent noninductive current ramp-up.

The toroidal field in NSTX-U is approximately double that in NSTX. The toroidal field benefits CHI by allowing higher

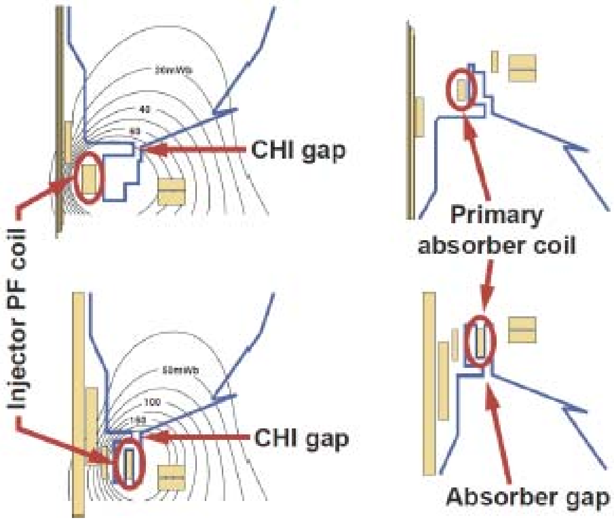

Fig. 3. Shown are the locations of the primary CHI injector and absorber coils in NSTX (top) and in NSTX-U (bottom). The absorber coils are used for generating a buffer magnetic flux to avoid contact of the growing CHI discharge with the upper divertor region.

current multiplication factors. Current multiplication is the ratio of the toroidal current to the injector current and scales as the ratio of the toroidal flux in the plasma to the injector flux. If the toroidal flux doubles (due to a doubling of the toroidal field), then the current multiplication factor would also double. Much more significant is the result that at higher values of the toroidal field, more poloidal flux can be injected at fixed values of the injector current. This is quite important because electrode sputtering, that releases low-Z impurities into the plasma discharge, increases with the number of charge carriers, which is proportional to the injector current. For NSTX-U, this means that approximately twice the amount of injector flux could be injected at NSTX level injector currents.

With improved electrode materials and wall coatings, this injector current could be further increased, and quite substantially, as seen by results from the much smaller HIT-II experiment [10], in which 30 kA of injector current could be driven without impurity issues. During the first two years of NSTX-U operation, CHI started discharges would rely on more complete coverage of the vessel walls with lithium evaporative coatings. Starting from 2017, discharges may also benefit from partial metallic divertor plates, which would reduce sputtering of low-Z impurities and from a divertor cryo pump, which would help reduce the density of CHI discharges by a process known as density pumpout that allowed spheromak plasmas to attain high electron temperatures.

Another source of low-Z impurities in CHI discharges is during the occurrence of a condition known as an absorber arc. This occurs when the upper toroidal insulator is shorted by the presence of plasma. This can happen if the growing CHI plasma makes good contact with the upper divertor gap. A weak contact is not an issue as many high-quality, high-current CHI discharges on NSTX were subjected to some absorber arcs. The intensity of the absorber arcs can be reduced by adding a buffer magnetic field in the upper divertor region to keep the CHI plasma from making good contact

TABLE I

PARAMETERS FOR THE PRIMARY PF COILS REQUIRED FOR INITIATING A CHI DISCHARGE IN NSTX AND NSTX-U

Coil	R (cm)	# Turns	L (mH)	R (mΩ)	kA-Turns (min)	kA-Turns (max)	kA.Turns/ms and Voltage (kV)
NSTX							
PFAB1	43.06	48	3.93	129.7	-48	48	+/- 4.8 [1 kV]
PFAB2	63.18	48	6.46	190.2	-48	48	+/- 4.8 [1 kV]
PF1B	30.5	32	0.673	3.15	0	+320	+19 [2 kV]
PF2L	80	28	1.98	7.32	-560	+560	+/- 25.3 [2 kV]
NSTX-U							
PF1AU,L	32.4	64	2.03	8.93	-460	1172	56.2 [2 kV]
PF1BU,L	40.4	32	1.14	9.19	-192	416	+45.8 [2 kV]
PF1CU,L	55.05	20	0.72	4.49	-100	318	+41.1 [2 kV]
PF2L	80	28	1.98	7.32	-308	420	+25.3 [2 kV]

with the upper divertor plates. The capability of these absorber buffer field coils, summarized in Table I (PFAB1 and PFAB2 on NSTX), to suppress absorber arcs, was well demonstrated in NSTX Transient CHI discharges [8]. Having a high-current slew rate in these coils may be advantageous as they can then be more quickly turned OFF, after the CHI discharge initiation process is over. Because of the much higher current magnitude and slew rates on the NSTX-U absorber buffer field coils, and much-improved positioning in relation to the upper divertor gap (PF1CU and PF1BU), they should be more effective in controlling absorber arcs. The requirements on the current slew rates can also be better studied on NSTX-U.

Starting from about 2017, the planned installation of a 1 MW 28 GHz electron cyclotron heating (ECH) system should allow CHI-started discharges to heat up to a few hundred electron volts. At these temperatures, the upgraded high harmonic fast wave (HHFW) system would be used to further increase the electron temperature to several hundred electron volts. TRANSP calculations suggest that at these plasma parameters, the new more tangential neutral beam system on NSTX-U should be able to drive sufficient current [11]. This in combination with bootstrap current over drive should allow the plasma current to ramp-up to the 1 MA steady-state current sustainment levels.

NSTX-U will also have two voltage subbing systems that limit transient voltage excursions between the inner vessel and ground and between outer vessel to ground potential. These consist of both a capacitor based snubber as well as metal oxide varistors (MOVs).

The power supply for a transient CHI discharge is a capacitor bank consisting of 10 capacitors in a parallel configuration. Each capacitor is rated for 2 kV operation and has a capacitance of 5 mF. The system is shown in Fig. 4 and the capacitor bank circuit and the snubber and MOV connections in Fig. 5. The capacitor bank is connected to the NSTX-U vessel using RG-218 coaxial cables. The bank is triggered using three ignitrons. These can be triggered at different times. These have a characteristic response time of about 1 μs, which is must faster than the required response time of about 0.1 ms. A typical configuration would initially discharge three capacitors using the first ignitron, followed

Fig. 4. NSTX-U transient CHI capacitor bank showing the 10 individual capacitors.

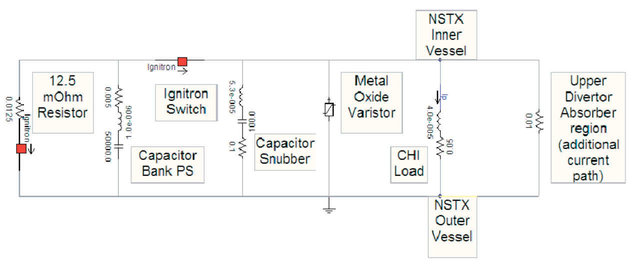

Fig. 5. Simplified circuit diagram of the transient CHI capacitor bank system on NSTX and NSTX-U.

by two more capacitors using the second ignitron and finally 2–3 capacitors would be discharged using the third ignitron. The number of capacitors in each subbank can be adjusted, as well as the bank trigger times to shape the injector voltage waveform. Expanding this capability to four modules is being considered for the 2017 and 2018 experimental campaign and will be implemented based on experimental needs assessed after the first two years of operations.

The system also includes a fourth ignitron that can be used to short the entire capacitor bank across a low resistance (typically 12.5 to 25 mOhm) to rapidly drain any remaining energy in the capacitor bank. This crowbar system is used to rapidly reduce the injector current by draining any left-over capacitor energy after the CHI discharge has filled the vessel. The arrangement for this system can be observed in Fig. 5.

On NSTX, the capacitor bank was operated at a maximum voltage of 1.7 kV. On NSTX-U initial experiments would be initiated at 2 kV. Then, during the 2017 to 2018 time period, the operating voltage of the capacitor bank would be increased up to 3 kV, as needed to allow injection of higher levels of poloidal magnetic flux to increase the magnitude of the CHI-started plasma current.

For transient CHI plasma start-up, the capacitor bank must satisfy these four requirements. The first requirement is that the capacitor bank must be capable of generating sufficient current to exceed the bubble burst current requirement. This requirement places a lower limit on the required injector current and is obtained by balancing the poloidal magnetic field line tension of the injector flux with the $J_{\text{pol}} \times B_{\text{toroidal}}$ force necessary to overcome the field line tension. It is given by the relation

$$I_g = 2\psi_g^2/(\mu_0^2 d^2 I_{TF}). \quad (1)$$

Here, ψ_g is the magnitude of the injector flux, d is the separation distance between the inner and outer legs of the injector flux footprint, and I_{TF} is the current through the center leg of the toroidal field coil [2]. For NSTX-U conditions, of $\psi_g = 82$ mWb, $d = 30$–40 cm, $I_{\text{TF}} = 130$ kA/turn*36turns, the required injector current is about 15 kA.

Circuit simulations for the capacitor bank to be used for the 2015 and 2016 campaigns shows that it is capable of generating over 25 kA injector current with sufficient current pulse width to satisfy the requirements for the first two years of NSTX-U transient CHI operations. The higher voltage capacitor bank planned for use during 2017 and 2018 will approximately double the capacitor bank energy. This in addition to the capability for discharging smaller parts of the full bank at separate times would provide the needed capability for voltage programming. More advanced power systems based on insulated-gate bipolar transistor switches were considered, and have been used to power a CHI injector current discharge on HIT-II [12], but their need does not appear to be necessary for NSTX-U transient CHI experiments, but may be reconsidered in the future.

The second requirement is related to the time needed for filling the vessel with the CHI generated plasma. This is given by the rate at which toroidal flux can be injected into the vessel. For an applied voltage of 2 kV, the rate of toroidal flux injection is 2 Wb/ms. To displace all of the toroidal flux inside the NSTX-U vessel, which is about 4.3 Wb at 1 T, about 2 ms would be required. The current pulse width of the injector current trace must therefore be more than this value. With a 3 kV capacitor bank, the time required to generate a CHI discharge would proportionally decrease to about 1.4 ms.

The third requirement is that there should be sufficient energy in the capacitor bank to fully ionize and heat the injected gas. This requirement also places an upper bound on the amount of gas that can be injected to initiate a transient CHI discharge. Typically for deuterium gas, 120 eV per ion is needed to fully ionize all of the injected gas and to increase its temperature to about 20 eV. For ∼2 torr·L injected into the vessel, this requires an energy of 1 kJ, which is much less than the energy stored in the capacitor bank. Here, it is useful to note that the 2 torr·L is about the same amount of gas NSTX used for initiating a standard inductive discharge. NSTX was able to successfully initiate CHI discharges with this level of gas injection. An added benefit of initiating a CHI discharge with such low levels of gas injection is that the resulting electron density is also low. On NSTX, typical CHI-started plasma electron densities were about 4×10^{18} #/m^3, which is less than the ECH cutoff density for 28 GHz ECH at 1 T. As a result these low density CHI plasma can not only be further heated using ECH, but because of the low electron density the line radiated power from residual low-Z impurities is also low, which allows these plasmas to burn through the oxygen radiation barrier. An useful note here is that it is easier to initiate CHI discharge at high-levels of injected gas. However, those discharges also radiate excessively and do not allow the resulting CHI discharge to heat-up. The highest current and least resistive CHI discharges on HIT-II were also obtained soon after fresh titanium gettering of the vessel walls. The system used two 50 g titanium sublimator balls purchased from National Electrostatics Corporation. 35 A of current were driven for 2 h through the resistive heater elements inside the balls. This resulted in about 10 g of titanium being deposited on the vessel walls. This wall conditioning technique on HIT-II allowed some of the injected gas to be absorbed by the walls, allowing a lower electron density discharge to be initiated. As the effect of the titanium wall conditioning diminished, the electron density in the CHI discharge increased from 0.7×10^{19} to 1.3×10^{19} m^3, and the magnitude of the plasma current decreased. This is shown in [13, Fig. 9]. Eventually, below a lower threshold, it not possible to obtain gas breakdown. For NSTX conditions, at the 1.7 kV operation voltage this level was about 2 torr·L of injected deuterium gas. The availability of a high-power ECH system on NSTX-U may allow this pressure to be further reduced, which may assist the CHI started plasma reaching a higher intrinsic electron temperature.

Finally, there should be sufficient energy in the capacitor bank to satisfy the eventual magnetic energy in the CHI plasma. For a 400 kA CHI discharge, the inductive stored magnetic energy is given as 0.5 $L_p I_p^2$. Here, L_p is the plasma inductance and I_p the plasma current. This must be less than 0.5 CV^2, where C is the bank capacitance and V the initial capacitor bank charging voltage. For a plasma with a normalized internal inductance of 0.35, as is the case with CHI started discharges [9], the plasma inductance L is given as $\mu_0 l_i$R/2. Here, R is major radius of the plasma, which is approximately the machine major radius [9]. For NSTX-U conditions, the stored magnetic energy is then 8 kJ, which is also much less than the capacitor bank energy.

IV. TSC Simulations

In support of the planned transient CHI studies on NSTX-U, we have started to develop a model using the TSC [14]–[16] 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 2-D Cartesian grid. Boundary conditions between plasma/vacuum/conductors are based on poloidal flux and tangential electric field being continuous across interfaces.

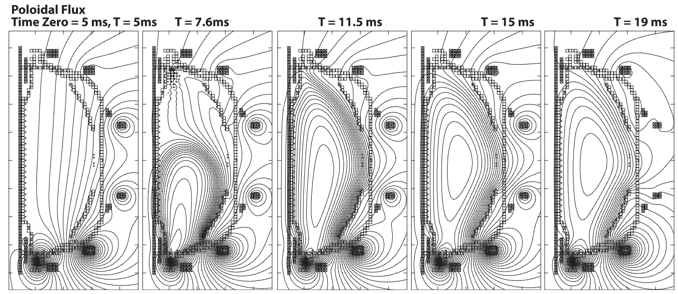

Fig. 6. Evolution of the injector flux in a transient CHI discharge initiation in the NSTX-U vessel geometry. The currents in the other coils (Fig. 7) are: PF1AL (−0.4 kA), PF2L (−0.35 kA), PF3L (−0.5 kA), and PF5 (−0.15 kA).

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.

For modeling 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 that 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 modeling strategy of adjusting the injector voltage 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 (1), 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 form NSTX [17]. This 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 [17] provides additional details showing consistency with earlier theoretical predictions [2]. It also shows that CHI scaling with toroidal field is favorable 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 (1).

These initial studies in the new NSTX-U vessel geometry, which are still in progress, at this time examines the evolution of the injected poloidal flux as the magnitude of the injector flux is changed. The model has also been simplified using constant in time, coil currents but thus far no optimizations have been conducted, such as for example using the

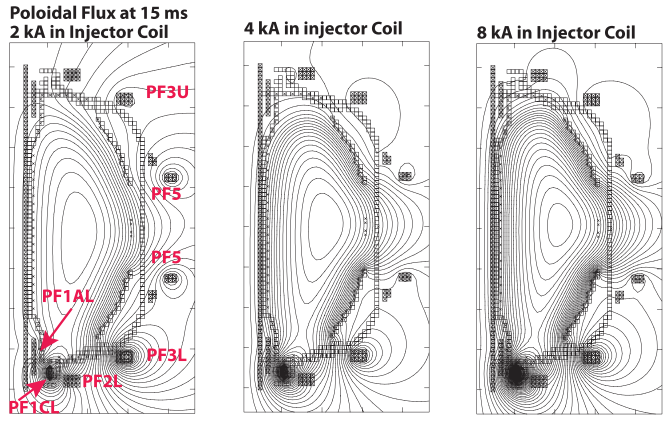

Fig. 7. Flux surface plots at 15 ms as the current in the primary injector flux coil (PF1CL) is increased from 2 to 4 and then to 8 kA.

appropriate vertical field magnitude and shaping required for the current in the CHI-produced plasma discharge or the appropriate voltage magnitude and pulse. Results from such detailed studies will described in a future publication after those studies are completed.

Fig. 6 shows the evolution of the injected flux starting from $t = 5$ ms, at which time the discharge is initiated. For these initial cases a 5 ms voltage pulse is applied across the injection electrodes, and of sufficient magnitude to allow the discharge the fill the vessel. A relatively low current of 2 kA is used in the primary CHI injector coil (the PF1C coil). Relatively, smaller levels of currents are used in the other nearby coils as noted in the figure caption. All other coils have zero currents. This is typical of the way initial transient CHI-started discharges could be expected to be initiated on NSTX-U. Fig. 7 shows the effect of increasing the current in the primary injector coil to 4 kA and then to 8 kA. The injector flux generated by this coil is directly proportional to the magnitude of the current driven in this coil. We note from Table I that the primary injector flux coil (PF1CL) has a maximum rating of 318 kA turns and it has 20 turns. Thus, the maximum current rating for this coil is 16 kA, which is projected to generate a maximum of 250 mWb of injector flux. The corresponding CHI-generated toroidal current for these three cases is 150, 300, and about 700 kA, respectively, as shown in Fig. 8, roughly reflecting the increased poloidal flux injection as the current in the injector coil is increased. Note from Fig. 7 that the higher current discharges appear to bulge out from the mid-plane region suggesting that the currents in the PF5 and PF3 coils for these two cases are not quite appropriate in this simulation. In addition, the toroidal current trace for the lowest current discharge shows the peak plasma current to flatten out during the peak current phase. This is similar to the shape of experimentally generated toroidal currents in NSTX and results because the applied injector voltage magnitude and temporal shape is such that the CHI drive is gradually and correctly reduced as the CHI-produced plasma fills the vessel. In contrast, for the other two higher current cases, and especially for the case with 8 kA in the PF1C coil, the toroidal current is sharply peaked suggesting that the applied voltage is still too high after the

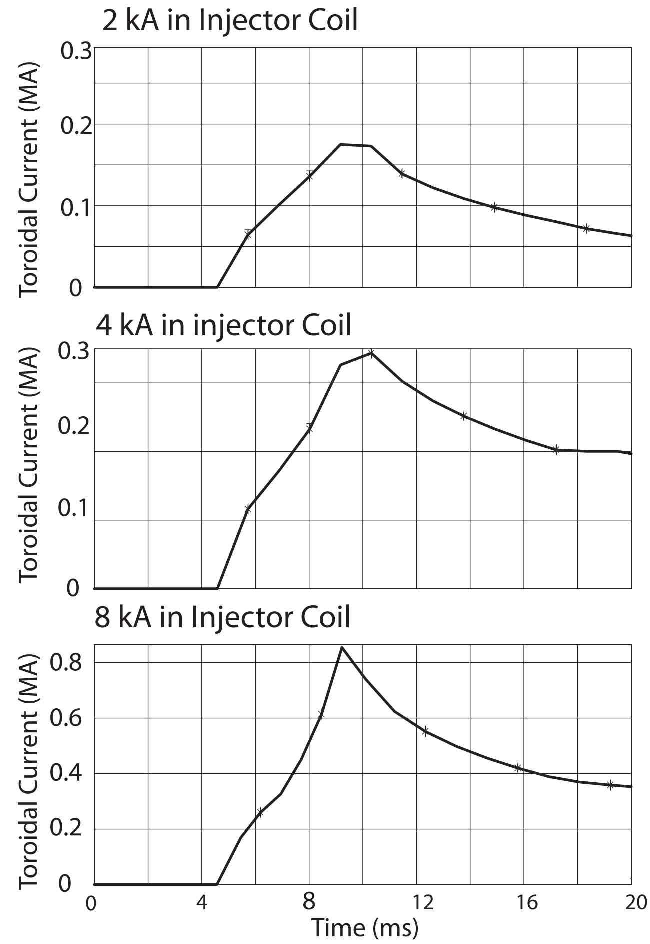

Fig. 8. CHI-produced toroidal current for the cases shown in Fig. 7.

plasma has filled the vessel. These optimization studies will be the subject of future work.

V. Conclusion

The method of transient CHI was originally developed on the HIT-II experiment at the University of Washington and later implemented on the much larger NSTX device at PPPL. On NSTX, the method generated 200 kA of high-quality closed flux plasma, and when coupled to induction the plasma current ramped up to 1 MA with substantial savings of the central solenoid flux. Other CHI-started discharges on NSTX, after coupling to induction transitioned to an H-mode demonstrating compatibility with high-performance plasma operation.

On NSTX-U, transient CHI will be used as the front end of a current ramp-up scenario, in which a combination of neutral beams and HHFW will be used to noninductively ramp the plasma current from the 400 kA CHI produced levels to 1 MA, where it will be noninductively sustained.

Several hardware improvements to the CHI system on NSTX-U should enable CHI start-up in excess of the projected 400 kA current level. These new system upgrades are (1) more than a factor of 2.5 higher injector flux, factor of two increase in the toroidal field, more complete lithium coverage of the NSTX-U vessel, up to a factor of 1.5 increase in the capacitor bank operating voltage, 1 MW 28 GHz ECH system, and eventually metallic divertor plates and a cryo pump. These in addition to the new second more tangential neutral beam system should allow NSTX-U to develop scenarios for full noninductive plasma start-up and current ramp-up in support of a FNSF.

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Authors' photographs and biographies not available at the time of publication.