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The favorable properties of the spherical torus (ST) arise from its very small aspect ratio. Methods for initiating the plasma current without relying on induction from a central solenoid are essential for the viability of the ST concept. In steady state tokamaks, the central solenoid can be dispensed with if suitable methods for initiating the plasma current are on hand. Coaxial helicity injection (CHI) is a promising candidate for solenoid-free plasma current startup in STs and tokamaks. Experiments on the Helicity Injected Torus (HIT-II) machine at the University of Washington [T. R. Jarboe, Fusion Technol. **15**, 7 (1989)] have demonstrated the capability of a new method, referred to as *transient* CHI, to produce a high quality closed-flux equilibrium that has been successfully coupled to induction demonstrating that this new plasma current startup method is compatible with the conventional inductive method. This paper presents physics requirements for implementing this method in STs and tokamaks and supporting experimental results from the HIT-II device. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2437115]

I. INTRODUCTION

The spherical torus (ST) is a magnetic confinement concept that has the advantages of high beta and a projected high fraction of bootstrap current drive.[1] The favorable properties of the ST arise from its very small aspect ratio. However, such devices have very restricted space for a central solenoid, which restricts the inductive pulse duration, making sustained noninductive operation necessary. Elimination of the central solenoid is essential for the viability of the ST concept and considered very important for the next generation of ST experiments. Thus, development of methods to initiate and sustain a ST discharge without reliance on the central solenoid is an essential element of the ST development path.[2] Some advanced tokamak designs also eliminate the central solenoid to save cost and simplify the reactor design, as this expensive component is needed only during the initial discharge initiation and current ramp-up phases.[3]

Coaxial helicity injection (CHI) is a promising candidate both for plasma startup and for edge current drive during the sustained phase. The possibility of using CHI in a ST was first proposed in the late 1980s.[4] Several STs have used helicity injection for solenoid-free toroidal current generation. These include experiments conducted on the Current Drive Experiment-Upgrade (CDX-U) at the Princeton Plasma Physics Laboratory (PPPL),[5] Proto-Helicity Injected Torus and the Helicity Injected Torus, I (HIT-I) at the University of Washington.[6] The Helicity Injected Spherical Torus in Japan and the SPHEX device in the UK.[7,8] All these devices, with the exception of CDX-U, used CHI in a configuration referred to as *steady-state* CHI. The CHI method drives current on open field lines creating a hollow current density profile in the poloidal (R-Z) plane. Taylor relaxation[9] predicts a flattening of this current profile, leading to current being driven throughout the volume, including on closed field lines. Current penetration to the interior is needed for usefully coupling CHI to other current drive methods and to provide CHI produced sustainment current during an extended noninductive phase. Such a process that relies on relaxation current drive has the potential for continuous steady-state current drive in STs and tokamaks. However, discharges using the steady-state method have yet to demonstrate successful coupling of the CHI-initiated discharge to a conventional current drive method such as induction from the central solenoid. Successful coupling to induction of plasma currents produced using any new method is an important step to show that the quality of currents produced using the new startup method is compatible with the well-established conventional plasma current startup method.

It was generally believed that the development of non-axisymmetric plasma perturbations are needed for plasma startup using the CHI process. Indeed this technique was initially used in the National Spherical Torus Experiment (NSTX).[10] However, in a significant new development during the past three years, it was shown that for the purpose of plasma startup, axisymmetric reconnection is adequate for producing a high quality startup plasma. This new method referred to as *transient* CHI has been highly successful on the HIT-II experiment.[11] On the HIT-II experiment, transient CHI has been used to successfully couple a CHI started discharge to induction. The method is simple and highly reproducible and has allowed HIT-II consistently to produce higher current discharges than what was possible by induction alone. Using transient CHI for initial plasma startup, HIT-II has produced record plasma currents of nearly 300 kA using only 0.052 V s of the central transformer flux.[12] These new results have motivated NSTX to modify the CHI hardware on NSTX to implement transient CHI.

Section II describes the CHI system components on HIT-II. Section III describes the requirements for the implementation of the transient CHI process. Section IV presents experimental results that show consistency with these requirements. Section V is a discussion of the experimental results. The final section is a brief summary of the most important transient CHI results obtained on HIT-II. This paper extends the results of previous work[11,12] by providing the physics requirements for transient CHI startup and by providing considerably more experimental data, including Thomson scattering temperature and density measurements, EFIT equilibrium reconstructions and a comparison of the CHI startup plasma's radiated power to the input inductive power needed for successful coupling of CHI started discharges to inductive drive.

II. IMPLEMENTATION OF CHI IN HIT-II

The nominal HIT-II machine parameters are: major/minor radii of 0.30/0.20 m, elongation ≤ 1.5, and a plasma volume of 0.4 m^3. The stainless steel vacuum vessel of HIT-II is fitted with toroidal ceramic breaks at the top and bottom so that the central column is insulated from the outer wall and the outer vessel components.[6] A detailed description of the HIT-II experiment is given elsewhere.[13] These toroidal ceramic insulators also act as vacuum surfaces. The poloidal field coils located beneath the lower part of the machine are used to produce poloidal flux that connects the inner and outer parts of the machine. This is referred to as the injector flux. When voltage is applied to the inner and outer vessel components, in the presence of a plasma, currents can flow along these field lines from the lower outer vessel region to the lower inner vessel. In a tokamak, the lower inner divertor plates would be used as the inner electrode. Correspondingly, the lower outer divertor plates would be used as the outer electrode, for example as on NSTX.[10]

The lower gap connected by the poloidal field is referred to as the injector and the complementary upper gap as the absorber because when voltage is applied toroidal flux flows out of the injector and into the absorber. On HIT-II, these poloidal field coils have been used for the generation of up to 16 mWb of injector flux, defined as $\int\int B \cdot dS$, where the surface of integration is over the entire center stack.

The operational sequence for CHI involves first energizing the toroidal field coils and the CHI injector coils to produce the desired static flux conditions in the injector region. The CHI voltage is then applied to the inner and outer vessel components and a preprogrammed amount of gas is injected in the injector region. These conditions cause the gas in the injector region to ionize and result in currents flowing along helical magnetic field lines connecting the injector electrodes. The ratio of the applied toroidal field to the poloidal field causes the current in the plasma to develop a strong toroidal component, the beginning of the desired toroidal plasma current. If the injector current exceeds a threshold value, the resulting ΔB_{tor}^2, $(\mathbf{J}_{pol} \times \mathbf{B}_{tor})$, stress across the current layer exceeds the field-line tension of the injector flux causing the helicity and plasma in the injector region to move into the main torus chamber. Once extended into the vessel, currents need to be driven in the external poloidal field coils for equilibrium position control.

For transient CHI, a capacitor bank is connected across the inner and outer vessel components to drive current along field lines that connect the inner and outer vessel components in the injector. The current produced by the capacitor power system is defined as the injector current. The toroidal current measured by the machine plasma current Rogowskii coil is referred to as the plasma current, which would in general be amplified many times over the injector current.

III. TRANSIENT CHI START-UP

A feature of CHI plasma current generation using this method is that unambiguous flux closure can be demonstrated by the persistence of toroidal plasma current after the injector current has been reduced to zero. This is because any toroidal current that remains after the external driving circuit has been fully turned off can only result from the presence of a decaying closed flux equilibrium. Closed flux is achieved by appropriate programming of the injector current, which can be easily achieved using a small capacitor-based power system. The capacitor bank is sized so that the energy in the capacitor bank mostly drains by the time the CHI produced plasma fully elongates. This causes the expanding plasma column to detach from the injector region, through a process of 2D axisymmetric reconnection and produce closed flux, analogous to the detachment of a solar flare on the surface of the sun. Most of the injector flux then reconnects the injector electrodes again, the short way around and some of the remaining capacitor bank energy would be dissipated along these field lines, in the private flux region.

Requirements for transient CHI start-up: The basis of helicity injection current drive is that magnetic field energy decays faster than helicity and that the configuration tends to relax towards a state of minimum energy while conserving helicity. A requirement for successful CHI current drive is that the energy per unit helicity of the injected helicity must be higher than that dissipated by the equilibrium ($\lambda_{inj} > \lambda_{tokamak}$, where $\lambda_{inj} = \mu_0 I_{inj} / \psi_{inj}$ and $\lambda_{tokamak} = \mu_0 I_P / \phi_T$); and the injected linked flux must flow into the equilibrium volume. Here ψ_{inj} is the injector flux and ϕ_T is the toroidal flux inside the vessel. I_{inj} and I_P are the injector current provided by the capacitor bank system and the plasma current inside the vessel, respectively.

For the transient CHI process to work the CHI system must meet certain requirements. First there must be sufficient energy in the capacitor bank to produce the bubble-burst current. The bubble burst current requirement states that the injector current is given by $I_{inj} = 2\psi_{inj}^2 / [\mu_0^2 d^2 I_{TF}]$ where d is the footprint width of the injector flux.[4] In the case of HIT-II the lowest attainable footprint width is approximately the inner-outer electrode gap distance, which is about 9 cm.[13] I_{TF} is the total current in the toroidal field coil center leg. Thus for an injector flux value of 8 mWb and at 700 kA of current in the toroidal field coil, which corresponds to 0.43 T on axis, the capacitor circuit needs to supply approximately 15 kA of injector current to meet the bubble burst current requirement.

The second requirement is related to how quickly the CHI discharge can fill the vessel. This is dependent on the applied injector voltage as this sets the rate at which toroidal flux moves across the injector and absorber gaps. For nominal conditions of about 0.5 T on axis, there is about

100 mWb of toroidal flux inside the HIT-II vessel. For 1 kV across the injector electrodes, the time needed to displace all of the toroidal flux within the vacuum vessel is about 0.1 ms. The current risetime in the capacitor circuit must be longer than this. The capacitor needs to supply the volt seconds (V s) in the toroidal flux.

The third requirement is that there must be sufficient energy in the capacitor bank to fully ionize and heat the injected gas. Typically about 50 eV is needed per ion for ionization and about 60 eV per ion to increase the plasma temperature to 20 eV. Thus at least 110 eV is needed per ion to allow the plasma to reach modest electron temperatures. In present experiments, the amount of injected gas results in a vessel pressure of about 4×10^{-3} to 8×10^{-3} Torr. The HIT-II vessel volume is 500 l. Therefore between 0.002 and 0.004 Torr l of deuterium gas is injected for CHI discharge initiation. This corresponds to up to 7×10^{19} atoms of deuterium. Assuming a 25% energy coupling efficiency of the initial stored energy in the capacitor to the plasma, the capacitor bank energy must exceed 3 kJ.

The fourth condition is that the bank also must contain enough energy to provide the inductive energy in the CHI produced discharge, which is $\frac{1}{2}L_P I_p^2$. The inductance of the toroidal plasma current on typical closed flux surfaces in HIT-II is about 0.5 μH.[14] For example, 5 kJ of capacitor bank energy at 50% efficiency, gives a plasma current of about 100 kA.

A final requirement is that the flux footprints on the CHI electrodes should be sufficiently narrow compared to the minor diameter of the elongated plasma. This condition allows oppositely directed field lines to preferentially reconnect near the injector throat. If the flux footprints are too wide, an x-point would not be created in the region above the injector electrodes, and the vertical force balance will be dominated by currents on open field lines, so the flux will just pull back into the injector as the injector current drops. In a CHI discharge, during the discharge initiation phase, the vertical plasma equilibrium is strongly dictated by open field line currents, which are responsible for causing the injector flux to move into the vessel in the first place. If the flux footprints are closer together, as reconnection occurs near the injector throat, and the currents on the open field lines cease, a diverted equilibrium forms. The vertical force balance from currents on open field lines would diminish and currents on closed field lines will become increasingly dominant for vertical equilibrium, which would be controlled by suitable currents in the external poloidal field coils. On HIT-II the minimum in this ratio is approximately 0.2, which is determined by the vessel and injector designs. In general, the rapid flux feedback control makes this easier in HIT-II than NSTX.

Satisfying these requirements allows the creation of a resistively decaying closed-flux equilibrium. If this decaying plasma current is to be coupled to another current drive method, then it is also necessary to satisfy an additional energy balance condition, which states that the energy losses from the CHI produced plasma should be less than the available input power from the current drive method to which the CHI startup plasma is being coupled.

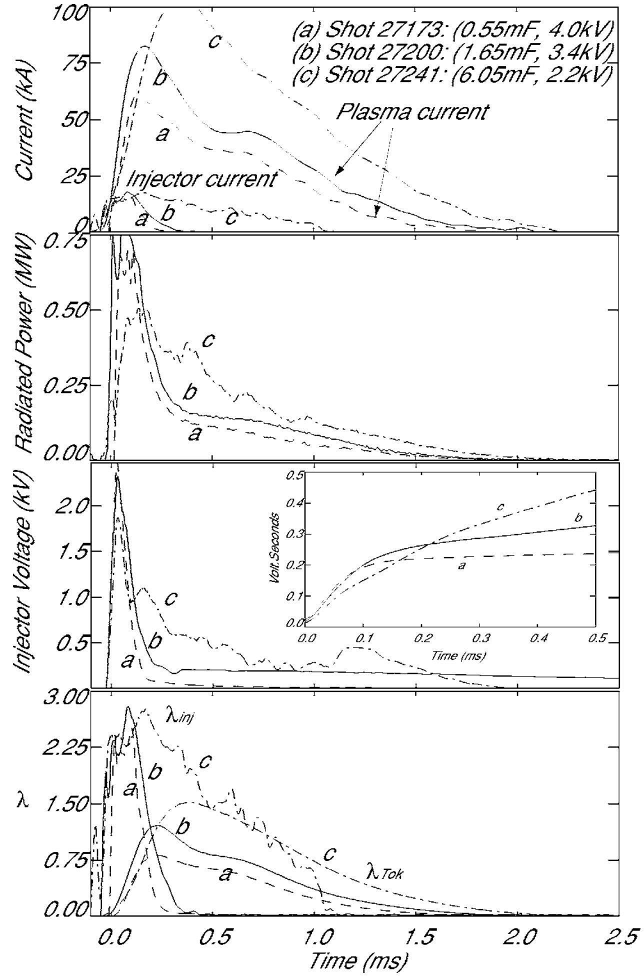

FIG. 1. The plasma and injector currents obtained using a large variation in the capacitor bank size, and the corresponding traces for the radiated power, injector voltage (with the injector V s shown in the inset) and the injector and tokamak λ.

IV. EXPERIMENTAL RESULTS

Figure 1 shows the plasma and injector currents obtained using a large variation in the capacitor bank size. A single capacitor has a capacitance of 550 μF. The injector and toroidal flux are held constant. The figure also shows the radiated power from the resulting plasma discharge, the voltage across the injector electrodes, and the injector V s. The last frame shows the injector and tokamak λ. For each case, the capacitor bank voltage that maximizes the resulting toroidal current during the current decay phase is chosen.

Figure 1 also shows that the attained plasma current increases as the size of the capacitor bank is increased. However if one were to use, as a figure of merit, the amount of plasma current that is left over after the CHI injector is no longer being actively driven, then the maximum obtained plasma current occurs for the three capacitor configuration. The time at which the injector is no longer injecting power is the time at which the injector current has been reduced to zero. The figure shows that for the three capacitor case, at the time of zero injector current at about 0.3 ms, about 60 kA of toroidal current remains. For the eleven capacitor configuration, at the time of zero injector current only about 40 kA

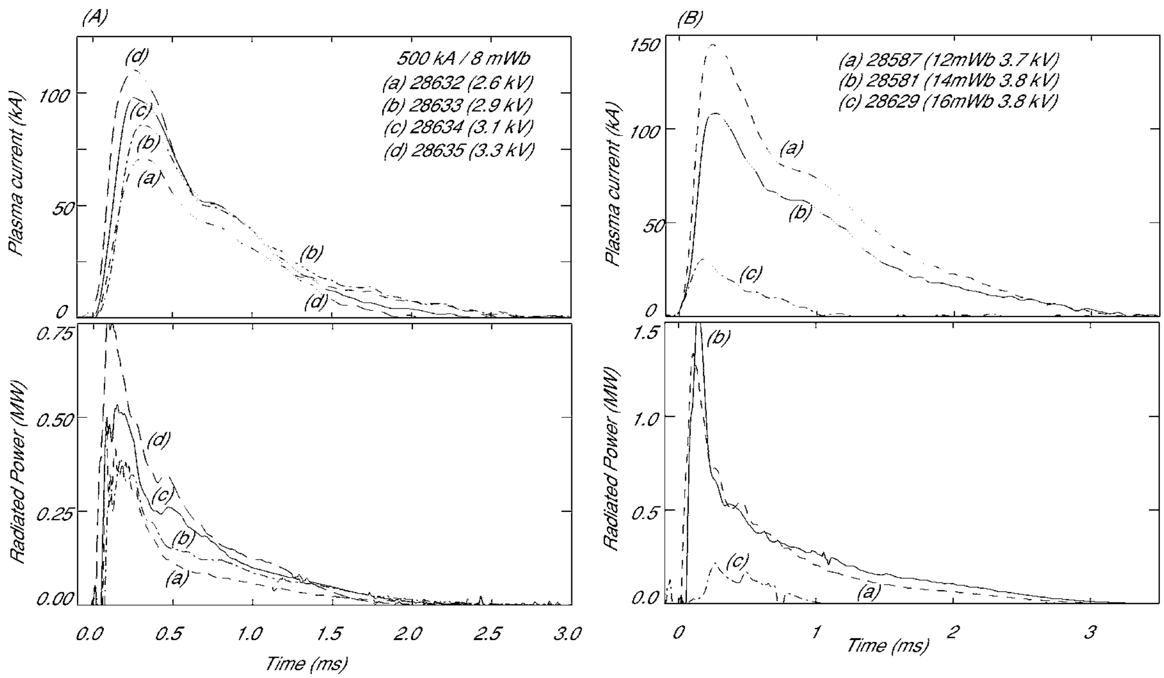

FIG. 2. (A) The result of increasing the capacitor bank voltage at fixed values of the injector flux and toroidal flux and (B) the effect of increasing the injector flux at a fixed value of the toroidal flux.

remains. Discharges with a single capacitor perform nearly as good as the three capacitor case, but the performance is below that of the optimum three capacitor case. In these discharges, the capacitor bank voltage is chosen so as to maximize the plasma current leftover after the injector current is reduced to zero. The effect of choosing a different value of the capacitor bank voltage is described below.

The injector voltage traces and the injector V s trace show that in all three cases the capacitor bank size meets the requirements for having sufficient V s to displace the toroidal flux contained in the HIT-II vessel during the initial formation phase of the CHI discharge. For all these cases, about 100 mWb of toroidal flux is contained within the HIT-II vessel. The injector V s reaches this value during the first 50 μs.

Figure 2 shows the result of increasing the capacitor bank voltage at fixed values of the injector flux and toroidal flux. Shown also is the effect of increasing the injector flux at a fixed value of the toroidal flux and at nearly constant capacitor bank voltage.

Figure 2(A) shows that as the capacitor bank voltage is increased, the CHI produced plasma current increases. However, beyond some threshold in the capacitor bank voltage, although the resulting plasma current is higher, it decays at a faster rate so that the duration of current persistence is reduced. The traces show that at the higher voltage (shot 28635) the plasma current has essentially reduced to zero at 2.0 ms, while at a slightly lower voltage (shot 28633), the plasma current persists for a longer time. At much lower voltage, the current persistence may be long, as in this case, however, the magnitude of the closed flux current at the time the injector current is reduced to zero is lower.

Figure 2(B) shows that as the injector flux is increased, for similar values of the capacitor bank voltage the CHI produced plasma current decreases. At sufficiently high injector flux, the magnitude of the injector current is insufficient to pull enough of the flux into the vessel. One notices that as the injector flux is increased from 12 to 14 mWb, even though the capacitor bank voltage increases slightly, the plasma current reduces while the radiated power increases.

Figure 3 shows results from coupling a CHI produced discharge to induction from the central solenoid. The target CHI discharge is produced using two values of injector flux. The capacitor bank voltage and the toroidal flux are optimized to increase the current that usefully couples to induction. For comparison a CHI only discharge at 14 mWb injector flux and an inductive only discharge that uses the same loop voltage as that used to drive the CHI target discharge are also shown.

Figure 4 shows the injector and tokamak λ for the discharges from Fig. 3 which couple to induction. Shown also are the radiated power and the input Ohmic power during the coupling phase to inductive drive.

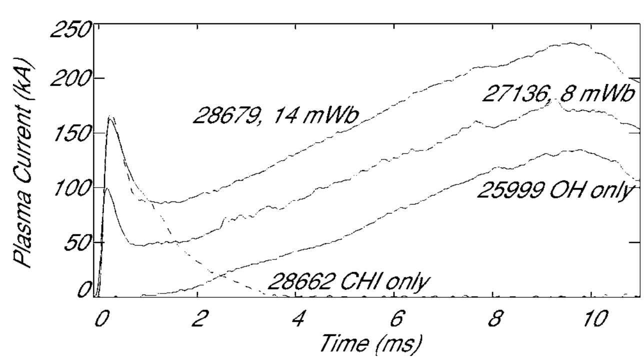

FIG. 3. Results from coupling a CHI produced discharge to induction from the central solenoid. Shots 25999, 28679, and 27136 and all have the same preprogrammed loop voltage history.

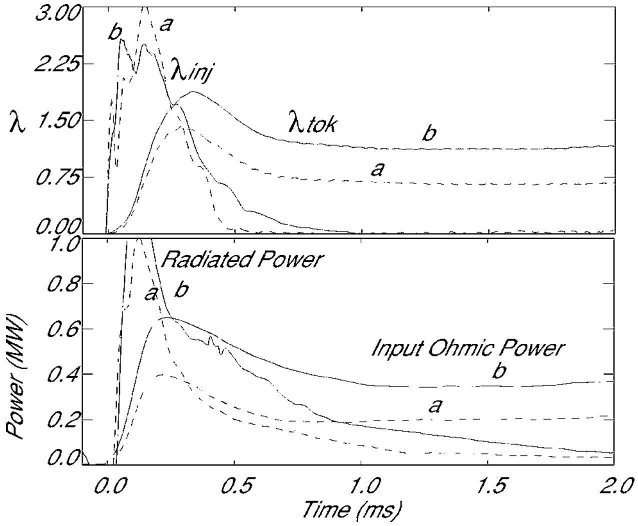

FIG. 4. The injector and tokamak λ for the discharges from Fig. 3 which couple to the induction, and the corresponding radiated power and the input Ohmic power during the coupling phase to inductive drive. Label a corresponds to shot 27136 and label b corresponds to shot 28679.

Figure 5 shows reconstructed equilibrium from EFIT during the coupling phase (2 and 3 ms) and during the current ramp-up phase (4 and 6 ms), for a high current discharge.

Figure 6 shows electron temperature and electron density profiles for several representative discharges with and without coupling to induction. The Thomson scattering system used for these measurements is a single time point system, therefore, several similar discharges were required to obtain profile evolution with time. The plasma current traces from these discharges are also shown.

V. DISCUSSION OF EXPERIMENTAL RESULTS

Figure 1 shows that for all discharges some of the CHI produced toroidal current is leftover after the injector current has been reduced to zero. After the time of zero injector current, the external CHI power supply is no longer driving the CHI injector circuit. Thus, the only plausible explanation for this leftover toroidal current is a decaying closed flux equilibrium, similar to the decay of an inductively produced discharge at zero loop voltage. In tokamak experiments the best measurements for current profiles are obtained from experimental measurements such as motional Stark effect, which could be used as constraints in equilibrium reconstruction calculations. On HIT-II because of the lack of such measurements, it is not possible to say with certainty how the current profile evolves. Because of the strong toroidal field in a ST, the electron current that is initially established at the edge may take a longer time (compared to spheromaks) to diffuse inward. In STs started by CHI the initial current profiles should be hollow as alluded to by the temperature profiles shown in Fig. 6. Diffusion of this current to the interior could further be slowed down by heating the edge of these plasmas. A better diagnosed machine such as NSTX is needed to understand current profile evolution of CHI started discharges when an external toroidal field is present.

A common feature of the radiated power signal is that soon after discharge initiation, during the plasma current ramp-up phase it increases to the 1 MW range. As the plasma current decays, the radiated power decreases rapidly to about 100–200 kW. It is useful to note that at about 0.3 ms, during the time when the three capacitor case shows 60 kA of closed flux current to be present, the radiated power level from the eleven capacitor configuration is two times higher. Furthermore, after the injector current is reduced to zero, the closed flux current from the three capacitor case has a longer current decay time. Since the eventual goal of discharges produced using the CHI process is to couple it to other current drive methods, it is desirable that both the current magnitude and the time duration for which this current persists both be as high as possible as this eases the requirements on the current drive system that would ramp up this initial current to higher levels. These results show that for a given injector flux and toroidal flux conditions, there is an optimum in the size of the capacitor bank

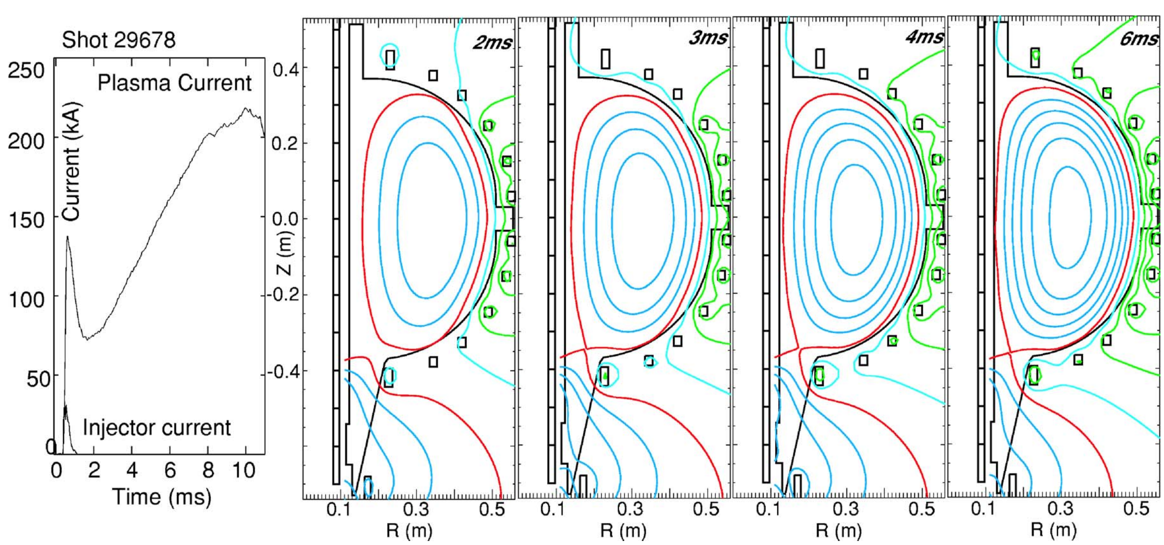

FIG. 5. EFIT reconstructions during the coupling phase (2 and 3 ms) and during the current ramp-up phase (4 and 6 ms), for a high current discharge.

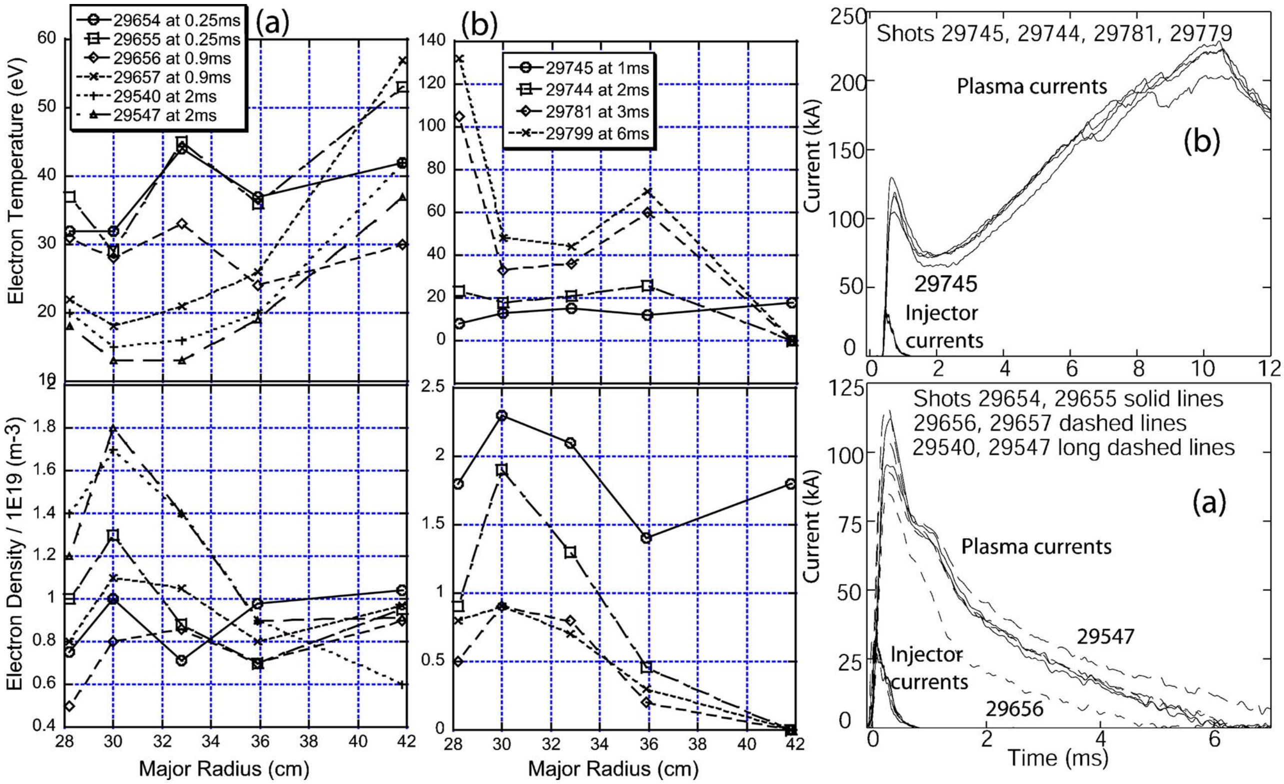

FIG. 6. The electron temperature and electron density profiles for several representative discharges (b) with and (a) without coupling to induction and the corresponding plasma and injector current traces.

that maximizes the amount of useful closed flux current that could be generated while minimizing the size of the capacitor bank power supply used to drive the injector circuit.

Traces for the injector and tokamak λ show that the injector λ remains higher than the tokamak λ during the CHI current ramp-up phase. Shortly after the CHI produced plasma current begins to decay, the injector λ drops below the threshold value needed for injecting helicity into the tokamak chamber. Thus for the time duration when $\lambda_{inj} < \lambda_{tokamak}$ even though some injector current is present, the condition for helicity injection states that this current must be dissipated on open field lines in the private flux region, and so it is not actively contributing to sustaining the current initially generated by CHI. Thus the amount of closed flux current remaining after the injector current is reduced to zero must represent a lower limit on the magnitude of the closed flux currents generated by the transient CHI process.

The radiated power traces in Fig. 2(A) between 2.9 and 3.3 kV capacitor bank charging voltage show almost a factor of 2 increase in the radiated power. The plasma with higher radiation is also more resistive and decays at a faster rate. Based on tokamak results, increased toroidal field must also contribute to a reduction in the current decay rate, however, in these experiments the contribution from the radiated power is much higher and there is insufficient data from controlled toroidal field scans to determine the lesser contribution from the toroidal field. The details of the nature of the increase in radiated power at higher voltages are clearly related to the nature of the electrode material and electrode physics and it is beyond the scope of the present study. However, the general result is that for a given electrode arrangement, there is a threshold level beyond which the plasma may become too resistive. In these experiments, a plasma that radiates more power than the power available from inductive heating is considered to be too resistive as the current in such plasmas cannot be ramped up to higher levels using the Ohmic solenoid.

At a given value of the toroidal flux, there is a limit to how much injector flux could be injected into the vessel, without making the resulting plasma too resistive. The results presented in Fig. 2 could be understood on the basis of early theoretical work[4] which provides the requirement for the bubble burst current, which is that $I_{inj}=2\psi_{inj}^2/[\mu_0^2 d^2 I_{TF}]$. This result states that at constant toroidal flux, or constant I_{TF}, the injector current required for satisfying the bubble burst condition, scales as the square of the injector flux. This is a strong scaling with injector flux. A higher value of the injector current means more charge carriers are bombarding electrode surfaces. Clearly for all electrode materials there are limits to surface power deposition values beyond which increased outgassing or other factors could result in a more resistive plasma being generated. The bubble burst current requirement also states that if the toroidal field were to be increased, then the required injector current to pull the same amount of injector flux decreases. However, at higher toroidal flux, the impedance of the injector circuit increases so that a higher capacitor bank voltage is required. Thus there is an optimization between the initial capacitor bank charging voltage and the toroidal flux that results in maximizing the amount of useful poloidal flux that can be injected.

Figure 3 shows the coupling of these optimized CHI discharges to induction. At 14 mWb of injector flux nearly twice as much closed flux current is produced than at 8 mWb of injector flux. The injector and tokamak λ traces, from Fig. 4(a) show that the requirement for $\lambda_{inj} > \lambda_{tokamak}$ is satisfied for both flux conditions, consistent with theoretical predictions.[15] Figure 4(b) shows that during the coupling to inductive drive, the input Ohmic power is comparable to the radiative power. Note that the plasma current ramps up only after the radiative power decreases below the input Ohmic power. Equilibrium reconstructions for shot 29678 show the poloidal flux to increase from 11 mWb at 2 ms during the coupling phase to 20 mWb at 6 ms as the plasma current increases due to inductive drive.

Electron temperature measurements for transient CHI discharges show Te to be in the 20–50 eV range near the time of peak CHI produced plasma current when the injector is still being driven by the external capacitor circuit. During the current decay phase it drops to about 10–30 eV. When CHI produced discharges at higher injector flux are coupled to induction, electron temperatures during the initial hand-off to the Ohmic phase (1–3 ms) are in the 10–30 eV range, then they increase to over 100 eV during the inductive drive and the region of higher temperature moves towards the inner wall. It is useful to note that the CHI only discharges show a higher edge temperature, especially during the actively driven phase, and later the profiles becomes less hollow. This is consistent with the CHI process that initially drives current in the edge thereby providing more heating power in the edge. Electron densities are in the $0.5\text{–}2 \times 10^{19}\ \mathrm{m}^{-3}$ range, which are similar to the parameters in a conventional tokamak discharge with inductive drive. Here it is useful to note that the current is not being carried by an energetic tail, but by a bulk thermal electron population because no x rays are detected.

In these experiments, the OH discharges started by CHI have a higher final current because the OH discharges start with an initial closed flux equilibrium that contains substantial closed flux current of quality compatible with inductive operation. This raises the question of whether the inverse process, that of applying CHI edge current to a preformed inductive discharge would contribute to increasing the magnitude of edge current fraction. Coupling of CHI driven edge current to induction should occur due to Taylor relaxation.[9] Previous experiments on HIT-II have shown that in such discharges, the total toroidal current does increase after CHI edge current application,[12,16] however, from the HIT-II results it is not possible to say how much of this edge driven current flows on closed field lines. Well diagnosed experiments, such as NSTX, are needed to understand the current penetration physics in such experiments.

VI. CONCLUSIONS

The process of transient CHI has produced closed-flux plasma equilibrium of quality that is comparable to that produced by inductive operation. The physics requirements for initiation of a transient CHI discharge and experimental evidence showing successful current generation are: (a) the injector λ must be higher than the tokamak λ for helicity injection to occur, (b) the capacitor bank system must be capable of meeting the bubble burst current requirement, (c) the capacitor bank needs adequate energy and voltage to provide the (V s) needed to displace the toroidal flux within the vacuum vessel, (d) there must be adequate energy in the capacitor bank to both ionize and heat the injected gas, and (e) to provide the inductive energy stored in the CHI produced plasma discharge. Finally, (f) the radiative power from the resulting CHI produced discharge must be less than the available input power used for ramping up the current produced by CHI startup.

On HIT-II the method has been highly successful and has produced 100 kA of closed flux current that was retained during the inductive drive. The method is relatively easy to implement and the power system requirements are modest. It should be tried on large tokamaks and STs. It is being pursued on NSTX.

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