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Plasma startup in the National Spherical Torus Experiment using transient coaxial helicity injection[a)]

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A method of plasma current generation known as coaxial helicity injection (CHI) has been successfully applied in the National Spherical Torus Experiment [M. Ono, S. M. Kaye, Y.-K. M. Peng *et al.*, Nucl. Fusion **40**, 3Y 557 (2000)] to form closed, nested magnetic surfaces carrying a plasma current up to 160 kA. In some discharges the generated current persists for surprisingly long, ~400 ms. While the CHI method has previously been studied in smaller experiments, such as the Helicity Injected Tokamak (HIT-II) [R. Raman, T. R. Jarboe, B. A. Nelson *et al.*, Phys Rev. Lett. **90**, 075005 (2003)] at the University of Washington, the significance of these results are (a) demonstration of the process in a vessel volume thirty times larger than HIT-II on a size scale more comparable to a reactor, (b) a remarkable multiplication factor of 60 between the injected current and the achieved toroidal current, compared to six in previous experiments, and (c) for the first time, fast time scale visible imaging of the entire process that shows discharge formation, disconnection from the injector, and luminous structures consistent with the reconnection of magnetic field lines and closed flux surfaces. These significant results indicate favorable scaling with machine size.
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I. INTRODUCTION

The spherical torus[1] (ST) is a low aspect-ratio toroidal magnetic confinement concept that has the advantages of high beta and a high fraction of bootstrap current. Because of the low aspect ratio, elimination of the central solenoid is very important for the next generation of ST experiments and is essential for the viability of the ST concept as a reactor. Noninductive methods for plasma current startup and sustainment therefore become necessary. An alternate method for plasma startup could also reduce the cost of a future tokamak reactor as indicated by the ARIES design studies.[2] The National Spherical Torus Experiment (NSTX) is exploring the technique known as coaxial helicity injection (CHI) (Ref. 3) as a method to produce the initial plasma and sufficient toroidal plasma current to allow other methods of noninductive current generation and sustainment to be applied.

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.[3] Helicity injection current drive in a ST was first conducted on the Current Drive Experiment-Upgrade (CDX-U) at the Princeton Plasma Physics Laboratory (PPPL).[4] As a result of experiments conducted on the Proto-Helicity Injected Torus, and the Helicity Injected Torus-I (HIT-I) at the University of Washington[5] the concept gained support. These experiments used a thick conducting copper wall for equilibrium control of the CHI produced plasma configuration. Two other experiments followed, the Helicity Injected Spherical Torus (HIST) in Japan and the SPHEX device in the UK.[6,7] These devices also employed passive wall stabilization for equilibrium control and confirmed that CHI could be used in the presence of an external toroidal field for the generation of a plasma configuration. Later HIT was rebuilt as the HIT-II experiment, which extended CHI to a true ST device by employing poloidal field coils for equilibrium control. Later the method was adapted to the NSTX device, which employs standard tokamak components.[8]

The CHI method drives current initially on open field lines creating a current density profile in the poloidal (R-Z) plane that is hollow. Taylor relaxation[9] predicts a flattening of this current profile through a process of magnetic reconnection leading to current being driven throughout the volume, including 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.

Helicity injection current drive is based on the fact that because magnetic field energy decays faster than the helicity, the configuration tends to relax towards a state of minimum energy while conserving helicity. Helicity is the linkage of magnetic flux with magnetic flux and in toroidal geometry is given by $K=2\int \phi d\psi$, where ϕ is the toroidal flux inside a flux surface and ψ is the poloidal flux, defined to be zero at the wall. In general the rate of change of helicity is given by $dK/dt=2\int_{\text{vacuum}}\mathbf{E}\cdot\mathbf{B}dV-2\int_{\text{plasma}}\mathbf{E}\cdot\mathbf{B}dV$, where the first integral is calculated over the plasma volume V in the absence of

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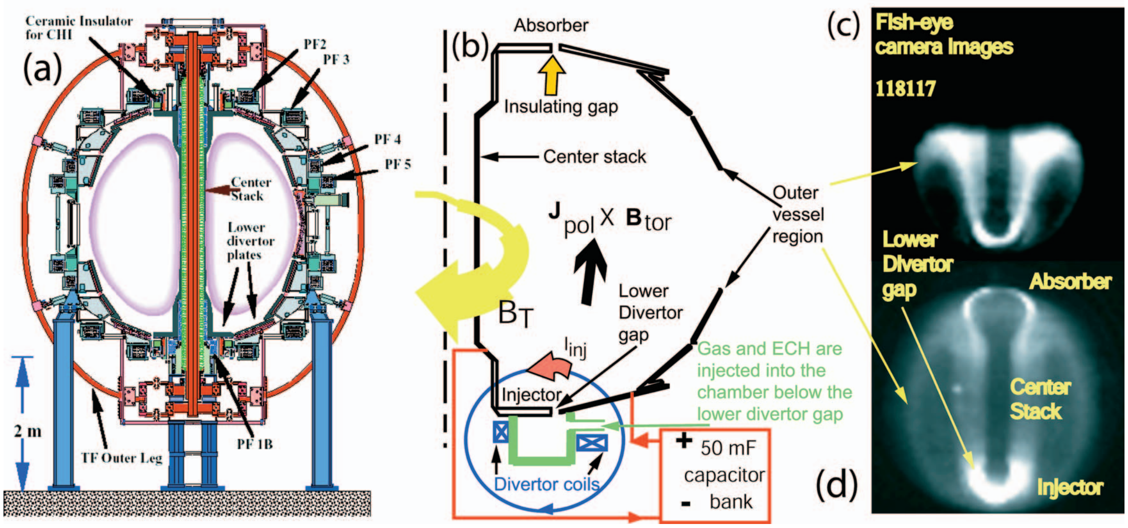

FIG. 1. (Color) (a) The NSTX machine layout showing the location of the toroidal insulator and external poloidal field coils. Shown also are (b) the NSTX machine components used for CHI startup in NSTX and fast camera fish eye images showing (c) discharge evolution from near the injector region and (d) later during the discharge. Both gas and 18 GHz microwave power are injected in to a 100 l toroidal cavity beneath the lower divertor plates. The gas, which is ionized by the microwaves, emerges from the gap between the lower divertor plates, which eases the requirements for breakdown when the main capacitor bank discharge is initiated.

plasma current but with the same magnetic field and flux boundary conditions that apply to the second integral, performed in the presence of the actual plasma.[10] The first integral can be thought of as the injection term and is equal to $2V_{\rm inj}\psi_{\rm inj}$ for CHI where $V_{\rm inj}$ is the voltage between the coaxial electrodes and $\psi_{\rm inj}$ is the flux that penetrates both electrodes. The second integral can be thought of as the resistive dissipation of helicity and is often called K/τ_K. A very important implication of the Taylor minimum energy principle is that $\int_{\rm pls}\eta\mathbf{j}\cdot\mathbf{B}dV=\int_{\rm pls}\mathbf{E}\cdot\mathbf{B}dV$. This is not to imply that $\mathbf{E}=\eta\mathbf{j}$ locally. For transformer current drive the helicity injection rate is $2V_{\rm loop}\phi_{\rm wall}$.

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 ($\lambda_{\rm inj}>\lambda_{\rm tokamak}$, where $\lambda_{\rm inj}=\mu_o I_{\rm inj}/\psi_{\rm inj}$ and $\lambda_{\rm tokamak}=\mu_o I_p/\phi_{\rm wall}$); and the injected linked flux must flow into the equilibrium volume.

It is generally accepted[11] that the development of nonaxisymmetric plasma perturbations is needed for plasma startup during which the CHI injector circuit is continuously driven under near steady-state conditions for some time ($t_{\rm pulse}>t_{L/R}$). This mode of CHI, also referred to as *steady-state* or *driven* CHI was the method initially tried on NSTX and used in other devices.[8,12] A significant development during the past three years has been the demonstration of a new mode of CHI operation on a ST, referred to as *transient* CHI (Ref. 13) analogous to fast formation ($t_{\rm pulse}\ll t_{L/R}$) on spheromaks.[14,15] This mode appears to involve an axisymmetric reconnection (or nearly axisymmetric reconnection) and has been highly successful on the HIT-II experiment. While the steady state approach is still needed for sustained edge current drive, transient CHI has been extremely successful on HIT-II for the purpose of plasma startup. Initial results from the successful application of the transient CHI method in NSTX is described in the subsequent sections.

Implementation of CHI in NSTX: The NSTX device is described in Ref. 16. In order to accommodate CHI, the stainless steel vacuum vessel (nominal major radius 0.85 m, volume 30 m^3) has separate inner and outer sections, electrically isolated from each other by toroidal ceramic rings at the top and bottom which also act as vacuum seals. The inner divertor plate, which is part of the center stack assembly, is then electrically separated from the outer divertor plate, which is attached to the outer vessel. This is illustrated in Fig. 1. For CHI, the poloidal field coils located beneath the lower insulated gap are used to produce poloidal flux connecting the lower inner and outer divertor plates, as indicated qualitatively by the circle in Fig. 1(b). When a small amount of deuterium gas is introduced into the chamber and a voltage (typically 1–2 kV) is applied between the plates, a discharge forms with current flowing in the plasma from the outer divertor plate to the inner lower divertor plate, as shown by the arrow in Fig. 1(b). In the presence of a toroidal field, the plasma current, which essentially flows along field lines, develops a toroidal component. The bright region at the top of Fig. 1(c) is the top of the CHI plasma that has extended to approximately the middle of the vessel at a time during the discharge when the plasma current is below the peak value. As the plasma current increases to near the peak value, the discharge further elongates vertically to fill the vessel as shown in Fig. 1(d). The bright ring shaped region at the top of this image is referred to as an absorber arc, a condition when part of the injector current bridges the upper divertor gap. We refer to the lower gap connected by the poloidal field 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.

The toroidal plasma current produced by CHI initially flows on open field lines joining the electrodes. In order to produce toroidal plasma current on closed flux surfaces magnetic reconnection must occur. In steady state, this reconnection depends on the development of some form of nonaxisymmetric plasma perturbation. In transient CHI, the initial poloidal field magnitude is chosen such that the plasma carrying the injected current rapidly expands into the chamber. When the injected current is rapidly decreased, magnetic reconnection occurs near the injection electrodes, with the toroidal plasma current forming closed flux surfaces. The method of transient CHI has now been successfully used in the NSTX producing an unambiguous demonstration of closed-flux current generation without the use of the central solenoid.

II. TRANSIENT CHI STARTUP

The first attempts to apply transient CHI in NSTX used the same programmable rectifier power supply that had been used for the earlier steady-state CHI experiments.[8] For transient CHI, it is advantageous to reduce the amount of gas injected for initiating the discharge in order to maximize the temperature of the resulting plasma. However, when the gas pressure was reduced, the time to breakdown increased and the thyristor switches for the rectifier power supplies were incapable of maintaining the voltage across the open circuit. A capacitor based power system was therefore installed, designed to satisfy several requirements for the transient CHI experiments in the NSTX.

The first requirement is that there must be sufficient energy in the capacitor bank to produce the "bubble-burst" current, i.e., the injector current I_{inj} at which the $J_{\mathrm{pol}} \times B_T$ force can overcome the field line tension in the injector, and cause the plasma to expand into the chamber above. The minimum injector current to meet the bubble burst condition is given as $I_{\mathrm{inj}}=2\psi_{\mathrm{inj}}^2/(\mu_o^2 d^2 I_{\mathrm{TF}})$, where I_{TF} is the current in the toroidal field coil and d is the width of injector flux "footprint"[3] on the electrodes. On the NSTX, the lower divertor coils located outside the vessel are used to control the width of the flux footprints. The dependence of the required injector current on the square of the injector flux and the inverse dependence on the current in the toroidal field coil has been confirmed in the HIT-II experiments and in previous NSTX experiments. For NSTX, injector currents from a few to about 30 kA are needed.

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 crosses the injector and absorber gaps $V_{\mathrm{inj}}=d\phi_{\mathrm{tor}}/dt$. For nominal NSTX conditions with 0.3 T on axis, there is about 1.4 Wb of toroidal flux inside the vessel. For 1 kV across the injector electrodes, the time needed to displace all of the toroidal flux within the vacuum vessel is about 1.4 ms. The pulse duration of the capacitor bank in NSTX satisfies this requirement.

The third requirement is that there should be sufficient electrical energy in the capacitor bank to fully ionize and heat all of the injected gas. Typically about 50 eV per ion is needed for ionization and about an additional 60 eV per ion to increase the plasma temperature to 20 eV. In previous experiments, the lowest amount of injected gas that could be injected and still achieve reliable breakdown was too high to achieve a reasonable temperature. To overcome this limitation, the gas injection for CHI was changed from four ports in the lower inner divertor plate to a single port in the small ($\sim$100 l) cavity below the toroidal gap between the plates. In addition 10 kW of 18 GHz microwave power was injected into the cavity to preionize the gas. These changes allowed breakdown to be achieved with much less total gas injected. The energy needed for ionizing and heating the injected gas was thereby reduced to a few kJ, less than that available in the bank.

The fourth requirement relates the maximum final toroidal plasma current I_p that can be produced to the energy available from the capacitor bank $\frac{1}{2}L_p I_p^2 < E_{\mathrm{cap}}=\frac{1}{2}CV^2$. The inductance of the toroidal plasma current on typical closed flux surfaces in NSTX is about 0.5 μH. For the present NSTX capacitor bank, the upper limit on the CHI produced current should be $I_p=400-600$ kA. A final requirement is that the flux footprints on the CHI electrodes should be sufficiently narrow. On the NSTX the lower divertor coils located outside the vessel are used to provide the injector flux shaping. The operational sequence for transient CHI in NSTX involves first energizing the toroidal field coils and the poloidal field coils to produce the desired flux conditions in the injector region. A preprogrammed amount of deuterium is then injected into the cavity below the gap between the inner and outer lower divertor plates. The 18 GHz preionization power is applied and the 15–40 mF capacitor bank at up to 1.75 kV charging voltage is connected by an ignition switch to the inner vessel and inner divertor plates, acting as the cathode, and the outer divertor plates and passive stabilizer plates, acting as the anode to form a discharge. After a programmed delay of 3–10 ms, when the plasma has expanded into the chamber and the toroidal plasma current is near its peak, the injector is short-circuited by a "crowbar" ignition causing the injector current to decay rapidly. The plasma column detaches from the injector region to form closed flux, analogous to the detachment of a solar flare on the surface of the sun. Most of the divertor flux then reconnects the divertor electrodes again by the shorter path. A feature of CHI plasma generation using this method is that flux closure can be demonstrated unambiguously by the persistence of plasma current after the injector current has been reduced to zero. During these experiments, the NSTX central solenoid was disconnected from its power supply.

III. EXPERIMENTAL RESULTS

In Fig. 2, we show traces for the plasma current, the injector current, and fast camera images at two different times during a typical CHI discharge. The discharge is initiated at 5 ms after which it rapidly grows to fill the vessel within about 2 ms. Note that the plasma current is amplified many times over the injector current. An absorber arc occurs around 8 ms, which increases the injector current to 17 kA. The absorber arc can be seen as the bright ring on the top of the camera image at 8 ms. For discharges that do not have an absorber arc, 2 kA of injector current is able to produce up to 120 kA of toroidal current, a current multiplication factor of 60. The image at 8 ms shows the plasma filling the vessel.

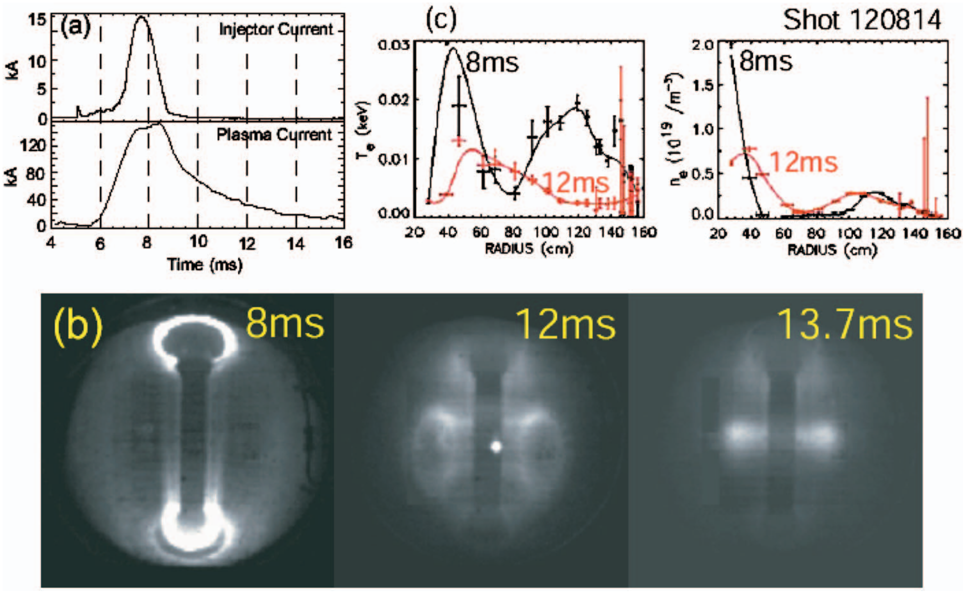

FIG. 2. (Color) Shown are (a) the plasma and injector current traces (b) fast camera images, and (c) the electron temperature and electron density profiles, at 8 and 12 ms from a CHI discharge in NSTX. The small bright glow near the middle of the vessel is light from a tungsten filament located near the wall inside the vessel.

Starting at about 9 ms, the discharge begins to disconnect from the injector electrodes after which the injector current falls essentially to zero while about 85 kA of toroidal plasma current remains. The 12 ms image shows an elongated dark region, which is surrounded by a brighter region, like usual visible-light images of tokamak plasmas. At 12 ms, the ring shaped plasma is clearly disconnected from both the injector and the upper divertor regions. As time progresses, the plasma further shrinks in size ending as a small diameter ring, as seen in the image at 13.7 ms. Since there is no injector current present after 10 ms, it is believed that the remaining plasma current is flowing in a closed magnetic flux configuration that decays on a resistive (L/R) time scale. In general, the Thomson scattering electron density and temperature profiles become less hollow as time progresses (see Fig. 2). This is expected since initially CHI drives current at the edge. After reconnection in the injector region, the current profile is expected to flatten, which should result in the profiles becoming less hollow. Taking the measured electron temperatures of about 15–20 eV and assuming Spitzer resistivity, and a typical plasma inductance of about $0.5-1$ μH, results in a current-decay e-folding time on the order of 5 ms, which is consistent with the observation that the current persists for about 10 ms after the injector current has been reduced to zero. During these discharges, the NSTX central solenoid was disconnected from its power supply.

Equilibrium reconstructions from discharge 120879 are shown in Fig. 3. Reconstructed flux surfaces compare well with the imaging adding support to the conclusion that closed flux surfaces have likely formed. The experimentally measured poloidal magnetic field at 40 sensors and poloidal flux at 44 flux loops distributed poloidally, are used in the computation of the Grad-Shafranov plasma equilibrium. The LRDFIT Grad-Shafranov equilibrium code[17] was used for these reconstructions. The code uses a circuit equation model of the plasma, vessel, and passive plate currents to constrain the equilibrium fits.

For comparison, the best result obtained during 2005 is also shown. By increasing the capacitor bank charging voltage from 1.5 kV (in 2005), to 1.7 kV (in 2006), it was possible to operate at higher values of the injector (poloidal) flux and at higher values of the toroidal field. This resulted in the magnitude of closed flux current increasing from 60 kA in 2005 to 160 kA during 2006.

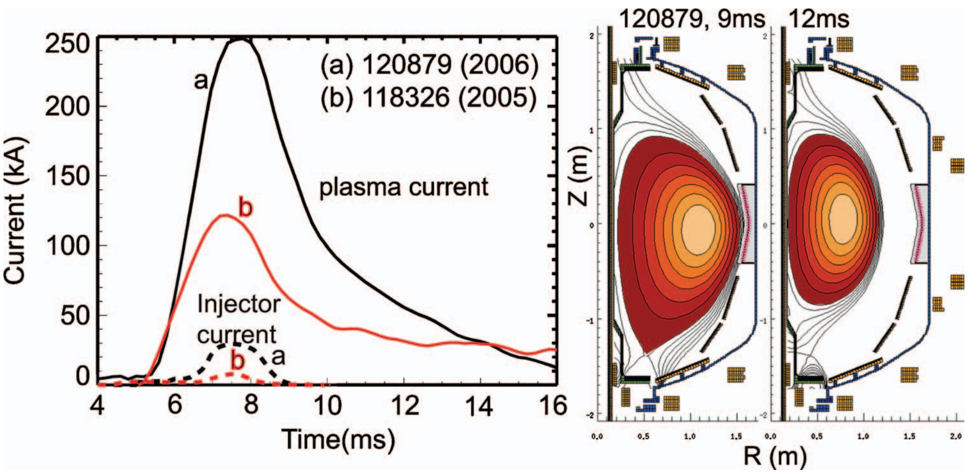

FIG. 3. (Color) Plasma current and injector current from discharges during 2005 and 2006. Operation at higher capacitor bank voltages and at higher values of the injector and toroidal flux resulted in the increase in the closed flux current to 160 kA during 2006. Equilibrium reconstructions at 9 and 12 ms for the higher current discharge (shot 120879) show the production of a closed flux equilibrium.

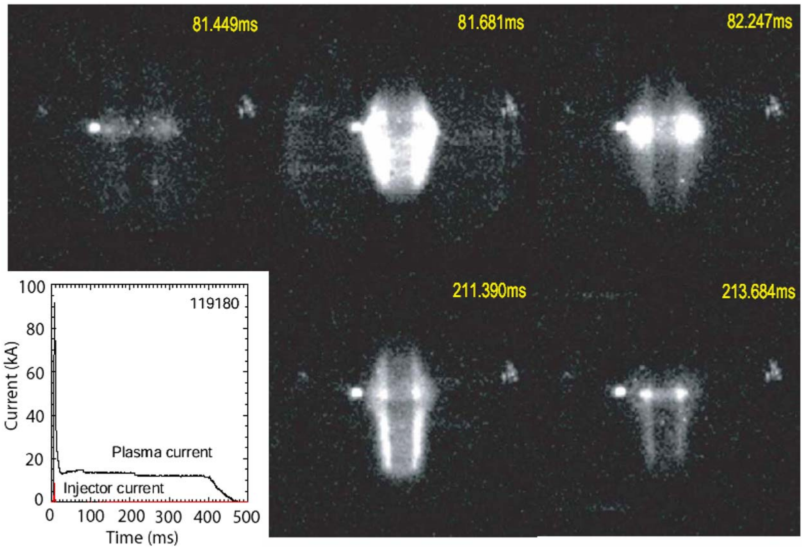

FIG. 4. (Color online) Fast camera images and plasma and injector current for a discharge that persisted for 400 ms. At 400 ms, the current in the poloidal field coils was ramped down to zero. At about 81 ms and 211 ms, the plasma discharge contacts the center stack resulting in visible emissions. Note that the plasma current drops after each contact with the wall. During the rest of the phase, the visible emission is very low, similar to that in the image at 81.449 ms.

An observation during 2006 was that all discharges had pronounced absorber arcs, which is the reason for the increase in injector current to well above 5 kA. This is because only a small portion of the capacitor bank energy is used in forming the discharge. In discharges without an absorber arc it was found that only 7 kJ of capacitor bank energy was needed to form a 60 kA closed flux discharge. Absorber arcs were avoided in the low current discharges as the CHI capacitor bank was operated at 1.5 kV and fewer capacitors were used (15 mF). As the capacitor bank charging voltage was increased it was found that significant conduction by the metal oxide varistors (MOVs) used as a snubber for filtering voltage spikes limited the actual available voltage to about 1.7 kV. To keep the capacitor bank voltage as high as possible 45 mF of capacitance was used, as with more capacitors the droop in voltage is reduced, allowing a higher voltage to be maintained for a longer time. This however, also resulted in much more unused energy being left in the capacitor bank circuit, which resulted in the pronounced absorber arcs. Future improvements to the charging power supply and the MOVs are being investigated so that the higher levels of closed flux current could be maintained, but with considerably reduced absorber arcing, which could be obtained using fewer capacitors. Nevertheless, these results verify the high current capability of CHI for plasma startup applications.

In other discharges, an example of which is shown in Fig. 4, the plasma current shrinks in size following the normal pattern, then becomes diffuse and spreads along the center stack. Because the plasma discharge now expands to fill a much larger volume along the center stack, its apparent brightness decreases. The discharge then begins to reduce in elongation along the center column and becomes a faint small ring that persists for as long as the equilibrium coil currents are maintained. In the longest duration discharge, a 15–20 kA plasma discharge remained for nearly 400 ms. This discharge is fairly robust, as during the period from 40 to 400 ms, one can occasionally see the discharge contacting the center stack producing a bright flash, then fully recovering and continuing. During some of these events, the plasma current drops as shown in Fig. 4. In some of these discharges, one can also see faint filaments of plasma that circulate at larger major radius. The density of these plasmas is below the measuring resolution of the Thomson scattering system, which is about 1×10^{12} cm^{-3}.

IV. DISCUSSION

Thomson scattering temperatures for the 80–100 kA plasmas indicate the temperature drops to about 50% in 4 ms (please see Fig. 5). This indicates an energy confinement time in the range of 3–5 ms for these plasmas. Simple zero-d power balance calculations indicate that with an input power of 200–300 kW, it should be possible to increase the electron temperature to about 100 eV, a temperature at which the NSTX High Harmonic Fast Wave (HHFW) heat-

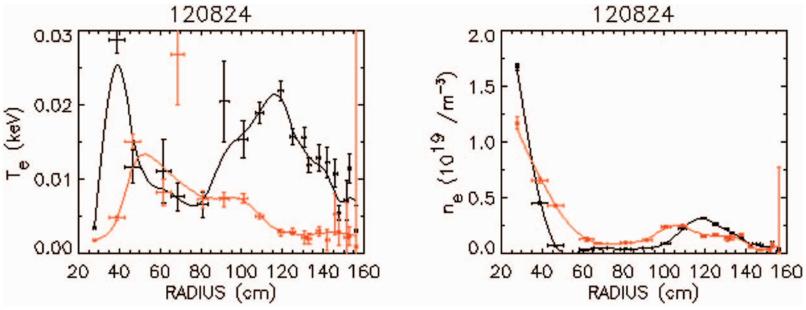

FIG. 5. (Color) Thomson scattering electron temperature for a low current (50–100 kA) discharge at 8 (black) and 12 ms (red). Initial temperatures are above the carbon radiation barrier temperature of 6 eV. The electron density is about 2×10^{18} m^{-3}.

ing system could contribute to further heating of these plasmas and possibly contribute to some noninductive current drive.

This estimate for the needed additional input power is also consistent with other measurements. For example for these plasmas, the radiated power during the current decay phase varies from less than 50 kW to a possible maximum of 200 kW. The radiated power, which should arise predominantly from line radiation from low-Z impurities (carbon and oxygen) could be reduced by further reducing the density of the CHI produced plasmas. The electron density of a CHI plasma could in principle be further reduced by using an inductive He plasma conditioning discharge prior to running a CHI plasma discharge, which should have an effect similar to the Ti-gettering wall conditioning technique used in the HIT-II machine. Both techniques increase the wall pumping capability, which reduces wall recycling and lowers the plasma electron density. For the same input power, a lower density would allow the electron temperature to further increase.

Microwave heating power in the range of 200 kW is also consistent with HIT-II observations that show that the inductive power, which during the coupling phase to CHI, is about 200 kW for low current plasmas (50 kA discharges) is adequate to couple to and heat the CHI target plasma and ramp the CHI produced closed flux plasma current to about twice the value of what is obtained using induction alone.[13]

A particularly important result is that on the NSTX, the ratio of the generated toroidal current to the injector current, exceeds 60. This is an order of magnitude larger than the previous experiment on HIT-II, and it extrapolates well to larger machines as the current multiplication is related to the ratio of the vacuum toroidal flux in the ST to the injector poloidal flux,[3,18] which increases with machine size. Thus in larger machines, this current multiplication ratio is not expected to decrease from what is achieved on the NSTX, but it could further improve. Additionally, results from HIT-II have shown that discharges with up to 30 kA of injector current are capable of producing plasma discharges that are capable of usefully coupling to inductive drive. Future machines operating at about 10–30 kA of injector current and 50–100 times current multiplication, should easily produce startup plasma currents that exceed a MA. A level of current at which well established noninductive current drive methods could ramp up the current to the needed levels.

Finally, an aspect of these discharges in NSTX is that they did not require any special vessel conditioning techniques. The observation on HIT-II was that the best discharges were produced immediately after titanium deposition on the vessel surfaces. After several discharges as the deposited titanium depleted, so did the quality of the CHI discharges. In addition, the present NSTX CHI configuration with divertor plates and relatively few poloidal field coils, is more prototypical of the future ST devices. The favorable helicity balance scaling and the prototypical divertor/poloidal field configuration as demonstrated on the NSTX bode well to future applications to fusion reactors.

V. CONCLUSIONS

Using the method of transient CHI in NSTX, about 160 kA of toroidal current has been produced in the NSTX. Current multiplication factor of 60 between the injected current and the toroidal current has been achieved, compared to six in previous experiments. High speed imaging and comparisons to equilibrium reconstructions support the existence of closed flux surfaces after formation. In this method a plasma current is rapidly produced by discharging a capacitor bank between coaxial electrodes in the presence of toroidal and poloidal magnetic fields. The initial poloidal field configuration is chosen such that the plasma rapidly expands into the chamber. When the injected current is rapidly decreased, magnetic reconnection is believed to occur near the injection electrodes, with the toroidal plasma current forming closed flux surfaces. Electron temperatures up to 20 eV have been measured in the plasma, similar to those seen in the HIT-II experiment. As time progresses, the measured profiles become less hollow, consistent with the expectations of CHI startup. Some discharges persist for very long durations, and seem to be limited only by the programmed decay in the vertical field. The significance of these results are (a) demonstration of the process in a vessel volume thirty times larger than HIT-II on a size scale more comparable to a reactor, (b) a remarkable multiplication factor of 60 between the injected current and the achieved toroidal current, compared to six in previous experiments, and (c) for the first time, fast time scale visible imaging of the entire process that shows discharge formation, disconnection from the injector and a resulting state consistent with reconnection of magnetic field lines and closed flux surfaces. These significant results indicate favorable scaling with machine size. Near term plans are to further increase the plasma current and to couple the CHI produced plasma to induction from the central solenoid. This would be followed by the application of up to 200 kW of microwave power to increase the electron temperature for coupling to other noninductive current drive methods.

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[1] M. Peng, Plasma Phys. Controlled Fusion **47**, B263 (2005).
[2] F. Najmabadi and the ARIES Team, Fusion Eng. Des. **41**, 365 (1998).
[3] T. R. Jarboe, Fusion Technol. **15**, 7 (1989).
[4] M. Ono, G. J. Greene, D. Darrow, C. Forest, H. Park, and T. H. Stix, Phys. Rev. Lett. **44**, 393 (1980).
[5] B. A. Nelson, T. R. Jarboe, A. K. Martin, D. J. Orvis, J. Xie, C. Zhang, and L. Zhou, Phys. Plasmas **2**, 2337 (1995).

[6] M. Nagata, T. Kanki, N. Fukumoto, and T. Uyama, Phys. Plasmas **10**, 2932 (2003).

[7] P. K. Browning, G. Cunningham, S. J. Gee, K. J. Gibson, D. A. Kitson, R. Martin, and M. G. Rusbridge, Phys. Rev. Lett. **68**, 1722 (1992).

[8] R. Raman, T. R. Jarboe, D. Mueller *et al.*, Nucl. Fusion **41**, 1081 (2001).

[9] J. B. Taylor, Rev. Mod. Phys. **58**, 741 (1986).

[10] T. R. Jarboe, Plasma Phys. Controlled Fusion **36**, 945 (1994).

[11] T. G. Cowling, Q. J. Mech. Appl. Math. **10**, 129 (1957).

[12] S. Woodruff, D. N. Hill, B. W. Stallard, R. Bulmer, B. Cohen, C. T. Holcomb, E. B. Hooper, H. S. McLean, J. Moller, and R. D. Wood, Phys. Rev. Lett. **90**, 095001 (2003).

[13] R. Raman, T. R. Jarboe, B. A. Nelson, V. A. Izzo, R. G. O'Neill, A. J. Redd, and R. J. Smith, Phys. Rev. Lett. **90**, 075005 (2003).

[14] H. S. McLean, S. Woodruff, E. B. Hooper, R. H. Bulmer, D. N. Hill, C. Holcomb, J. Moller, B. W. Stallard, R. D. Wood, and Z. Wang, Phys. Rev. Lett. **88**, 125004 (2002).

[15] C. W. Barnes, J. C. Fernandez, I. Henins, H. W. Hoida, T. R. Jarboe, S. O. Knox, G. J. Marklin, and K. F. McKenna, Phys. Fluids **29**, 3415 (1986).

[16] M. Ono, S. M. Kaye, Y.-K. M. Peng *et al.*, Nucl. Fusion **40**, 3Y 557 (2000).

[17] J. Menard (private communication, 2006).

[18] X. Z. Tang and A. H. Boozer, Phys. Plasmas **12**, 042113 (2005).