Demonstration of Tokamak Ohmic Flux Saving by Transient Coaxial Helicity Injection in the National Spherical Torus Experiment

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Transient coaxial helicity injection (CHI) started discharges in the National Spherical Torus Experiment (NSTX) have attained peak currents up to 300 kA and when coupled to induction, it has produced up to 200 kA additional current over inductive-only operation. CHI in NSTX has shown to be energetically quite efficient, producing a plasma current of about 10 A/J of capacitor bank energy. In addition, for the first time, the CHI-produced toroidal current that couples to induction continues to increase with the energy supplied by the CHI power supply at otherwise similar values of the injector flux, indicating the potential for substantial current generation capability by CHI in NSTX and in future toroidal devices.

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Toroidal magnetic configurations based on the tokamak concept might be simplified and their cost reduced if the central solenoid, which is a large engineering component in conventional tokamak reactor designs could be eliminated [1,2]. The central solenoid also requires extensive neutron shielding and places a lower limit on the achievable aspect ratio in reactor tokamak designs. Elimination of the central solenoid would provide greater flexibility in the selection of the aspect ratio and possibly lead to a simpler and less expensive reactor design as a result of the higher toroidal plasma beta that could be achieved at lower aspect ratio. In particular, due to the limited inboard space, the development of an acceptable solenoid-free plasma start-up method is highly important for the viability of the spherical torus (ST) reactor concept.

Coaxial helicity injection (CHI) has previously been used for spheromak formation [3–5], in reconnection merging experiments [6] and in ST plasma formation [7]. Initial transient CHI work on the National Spherical Torus Experiment (NSTX) demonstrated the generation of a closed-flux equilibrium using the transient CHI process [8]. While the closed-flux configuration formation is a necessary condition, a critical test for a viable solenoid-free tokamak start-up concept is the demonstration of high-quality tokamak plasma formation which is equivalent to that obtained with the central induction by a solenoid. For this test, it is necessary to demonstrate that the CHI tokamak formation technique actually reduces the solenoid flux consumption and produces equivalent quality tokamak plasmas. In particular, a concern for a CHI based tokamak plasma start-up has been the impurity generation from the electrodes involved in the CHI start-up. We report here a demonstration of the formation of a clean tokamak discharge using CHI through impurity control techniques which resulted in a significant Ohmic flux saving and produced equivalent quality tokamak plasmas. In addition, for the first time, as expected from the helicity balance model, the CHI-produced toroidal current that couples to induction continues to increase with the energy supplied by the CHI power supply at otherwise similar values of the injector flux indicating the potential for substantial current generation capability by CHI in NSTX and in future STs.

As shown in Fig. 1 and as described in Ref. [8], a transient CHI discharge is produced in NSTX by first energizing the poloidal field (PF) coils near the lower divertor plates, which are electrically insulated from each other, to generate field lines that connect the lower inner and outer coaxial rings of the divertor plates. Gas is injected in a chamber below the divertor plates and after a delay, voltage (typically 1.7 kV) is applied by connecting a capacitor bank across these plates. The gas emerging between the plates breaks down and current flows along field lines from the outer to the inner plate. As the injector current exceeds a threshold value known as the "bubble burst" current, the electromagnetic $J_{\mathrm{pol}} \times B_{\mathrm{tor}}$ force resulting from the current flowing along the poloidal field overcomes the field-line tension and the open field lines begin to extend into the vacuum vessel. The bubble burst current is given by the relation $I_{\mathrm{inj}} = 2\psi_{\mathrm{inj}}^2/(\mu_0^2 d^2 I_{\mathrm{TF}})$ [9], where ψ_{inj} is the poloidal flux at the injector insulating gap, I_{TF} is the total current in the toroidal field coil and d is the width of injector flux "footprint" on the electrodes. The lower divertor electrodes are referred to as the "injector" and the similarly insulated upper divertor plates are referred to as the "absorber". After the plasma fully fills the vessel, if the injector current is then rapidly reduced below the bubble-

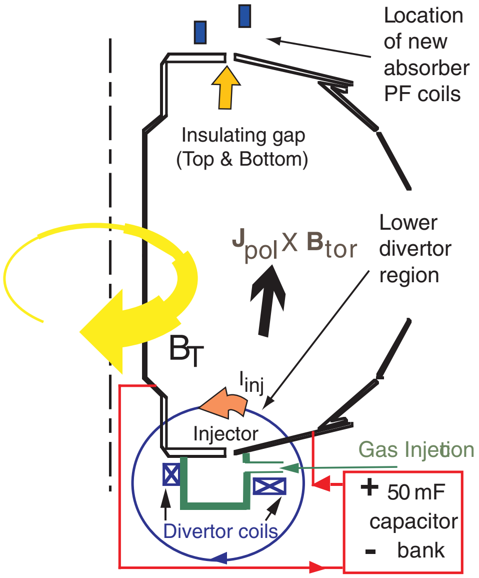

FIG. 1 (color). Schematic of the NSTX machine components including the location of the insulating gaps between the divertor plates, the lower divertor coils used for generating the CHI injector flux and the absorber poloidal field coils.

burst threshold, the plasma disconnects from the injector forming a closed field-line configuration which retains a significant toroidal current. If the expanding CHI-produced plasma reaches the absorber structure while voltage is still being applied across the electrodes, a secondary discharge can develop in the absorber. This is referred to as an "absorber arc" and it can present a much lower impedance than the injector. It is the toroidal plasma current component flowing along closed field lines after the injected current has been terminated that can be subsequently driven inductively to further increase its magnitude. In the experiments reported here, the following two impurity control techniques are found to be critical for the clean CHI start-up demonstration which is equivalent to and compatible with Ohmic start-up.

First, it is critical to clean the lower divertor plates (CHI electrodes) prior to the CHI discharges. In these experiments the lower divertor electrodes were cleaned by running about 30 400 ms long CHI discharges with increased poloidal flux connecting the lower divertor plates (the injector flux) and limiting the magnitude of the injector current to about 5 kA so that the resulting discharge stayed connected to the lower divertor plates. This electrode conditioning process reduced the level of low-Z impurities, particularly oxygen, measured spectroscopically during the CHI process. In addition, the recent CHI experiments made use of lithium coating of the plasma-facing components, including the CHI electrodes, by a pair of evaporator ovens mounted at the top of the vacuum chamber [10].

Second, two PF coils located in the upper divertor region were energized for the first time to provide a "buffer" flux to reduce contact of the growing CHI discharge with the upper divertor electrodes. In the absence of this buffer flux, once the CHI discharge contacted the upper (absorber) divertor electrodes, an absorber arc usually developed which generated undesirable impurities. This is illustrated in Fig. 2. Discharge 135622, which has no current in the absorber PF coils, shows no coupling to induction for otherwise identical conditions. An examination of the injector current trace shows the characteristic spike at 9 ms indicative of the occurrence of an absorber arc, which is absent for the discharge with the buffer flux applied. The occurrence of the absorber arc is also seen as a bright ring around the top of the center column in the fast camera image at 8.5 ms. On the other hand, in the discharge 135616 with buffer flux applied, the CHI-produced discharge couples well to induction and ramps up to 800 kA. Note that both discharges show nearly identical fast camera images just prior to the occurrence of the arc at 7.5 ms. At 20 ms, the discharge with the absorber arc shrinks in size and is still radiating in the visible spectrum whereas the discharge with no arc, because of its higher temperature, is no longer radiating in the visible spectrum. Traces for the oxygen line radiation signatures show that although the lower divertor oxygen levels are nearly the same for both cases, a dramatic increase in the upper divertor oxygen signal is seen when the absorber arc occurs. The central chord bolometer signal also shows significantly elevated levels of radiated power well after the absorber arc has ceased, indicating the presence of increased amounts of low-Z impurities, as is also apparent in the upper divertor oxygen signal.

The improvement in performance of CHI-started discharges as the size of the capacitor bank is increased is shown in Fig. 3. Each discharge benefitted from the use of 100 mg of lithium evaporation beforehand. With a single capacitor (5 mF), about 120 kA of plasma current is produced. At the higher levels of capacitor bank energy, not only does the initial current increase, but the current during induction is higher than with induction alone. This improvement is also reflected in the electron temperature which reached 50 eV for the first time during the CHI phase. The temperature remains high with increasing CHI power supply energy whereas it previously fell as the impurity level increased. This is the first such observation in NSTX that indicates that low-Z impurity levels in these plasmas are now at a sufficiently low level so that additional capacitor bank energy contributes to plasma heating rather than being lost through impurity line radiation. At the temperatures achieved, the oxygen radiation barrier is exceeded, thereby allowing the rapid ramp-up in the current when the induction is applied. These results indicate that the methods used for low-Z impurity control in NSTX have been effective. Further improvements are still possible, which should increase the CHI current start-up potential in NSTX.

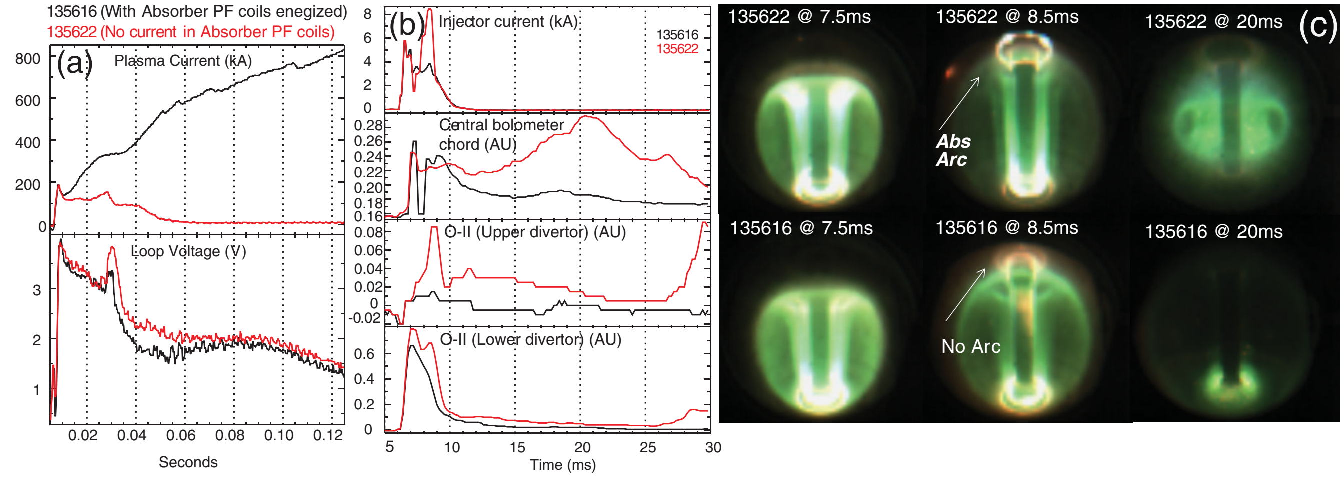

FIG. 2 (color). Shown are (a) the plasma current and preprogrammed loop voltage for two discharges. Discharge 135622 is a reference discharge in which the absorber PF coils were not energized. In discharge 135616 the absorber PF coils provided a buffer flux to the evolving CHI discharge. Also shown are (b) the injector current, signal from a central chord bolometer, the upper and lower divertor O-II signals. (c) Fish-eye camera images just prior to, during, and after the absorber arc for both discharges.

For the discharge shown in Fig. 3 using 15 mF (three capacitors), at 48 ms, nearly 200 kA of additional current is present and retained over the reference inductive-only discharge. All discharges had identical programming of the central solenoid loop voltage as seen in the second trace in Fig. 3(b). At 50 ms, 0.11 Wb of central solenoid flux has been applied. When applied to the CHI-started discharge (135614), the current reached 525 kA, whereas in the inductive-only discharge (135621), the current reached only 325 kA. As shown in Fig. 4, both the electron temperature and density profiles for the CHI initiated discharge (135614) were higher than for the reference inductive-only discharge so that the plasma pressure was nearly doubled. Discharge 135618 with four capacitors reached an initial peak of 300 kA, which is a record for transient CHI-started discharges in a ST or tokamak. The initial stored capacitor bank energy is 27 kJ, which is quite modest. Although this too subsequently shows better performance than the inductive-only discharge, it is not as good as that for the two and three capacitor cases. The reason for this is seen in Fig. 3(b), which shows that the constant value of buffer field that was used for all cases was inadequate for this higher current discharge as an absorber arc occurred and consequently there was additional impurity influx. Because

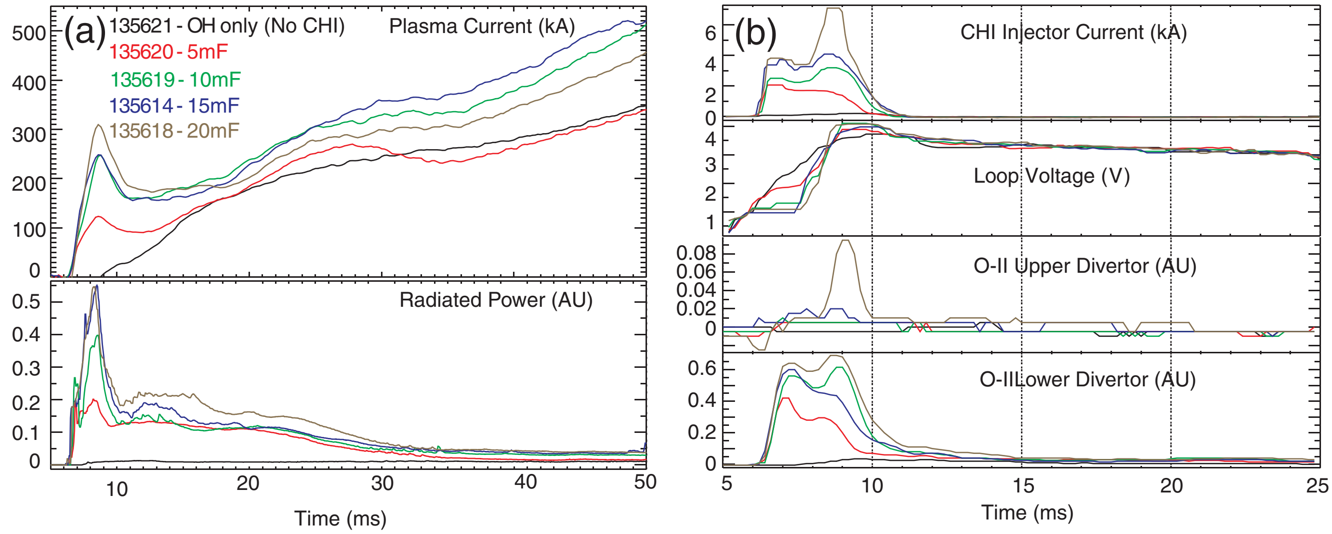

FIG. 3 (color). (a) Shown are plasma current and radiated power traces from a scan in which the size of the CHI capacitor bank power supply was increased from 5 to 20 mF. Discharge 135621 is a reference inductive-only discharge. (b) CHI injector current and spectroscopic traces for the four discharges.

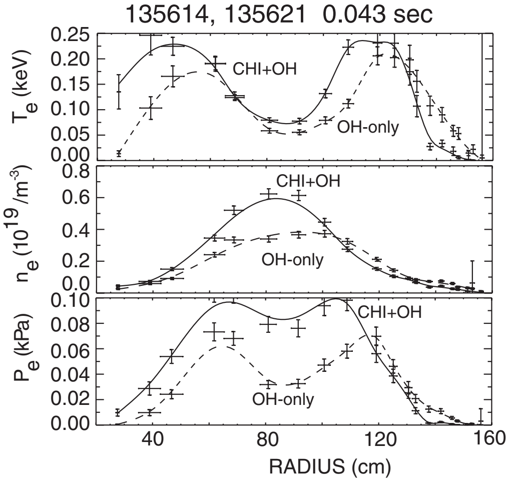

FIG. 4. Electron temperature, density, and pressure profile from a Thomson scattering diagnostic for a CHI-started discharge 135614 and a reference inductive-only discharge.

of this arc, not all of the 27 kJ is used to produce the CHI discharge, so that the energy efficiency is much better than 10 A/J. Clearly more buffer flux is required for the higher current CHI discharges but in these experiments, the absorber PF coil currents were limited by their power supplies. In Fig. 3(b), for discharge 135618, the injector current shows the pronounced current spike related to absorber arcing, there is a simultaneous increase in the upper divertor O-II signal, and the radiated power stays elevated.

For all cases shown in Fig. 3, the current multiplication at the time of the peak current during CHI is approximately that given theoretically by the flux multiplication ratio: $I_p = I_{\text{inj}}(\phi_{\text{plasma}}/\psi_{\text{injector}})$. Here ϕ_{plasma} is the total toroidal flux inside the plasma and ψ_{injector} is the injector poloidal flux measured as the poloidal flux that connects the lower inner CHI electrode to the outer electrode. For all these discharges at the time of CHI discharge initiation there is 20 mWb of injector flux connecting the lower divertor electrodes. At the toroidal field of 0.52 T used in these discharges, the maximum toroidal flux in the NSTX vessel is 2.0 Wb, so the theoretical maximum current multiplication is ~100. For the discharges in Fig. 3, the current multiplication ranges from 70 to 100. What is important about these results is that, even though the injector flux for all cases remains the same and all discharges have about the same value of current multiplication, the CHI-produced toroidal current continues to increase with increasing capacitor bank energy. The maximum achievable toroidal current in these discharges is limited by the influx of low-Z impurities that does increase with injector current. If the injector current could be doubled (for example, by doubling the number of capacitors), while maintaining a low influx of impurities, then, in principle an initial start-up current of about 600 kA should be realizable in NSTX. Theoretical analysis also indicates that this should be possible in NSTX [11]. It should be noted that the small HIT-II device, built solely to study CHI physics, was able to routinely run at 30 kA of injector current without encountering any impurity issues [12]. This suggests that the present injector current limits of about 4 kA on NSTX have considerable room for improvement. Moreover, the higher electron temperature trend of increasing CHI initiated plasma current implies that it should be feasible to directly couple the high harmonic fast wave heating [13] to further ramp-up the plasma current noninductively.

In summary, significant improvements to CHI performance were made possible by new wall and electrode conditioning methods aimed at reducing low-Z impurity influx into the plasma discharge and by applying additional buffer flux with a pair of absorber poloidal field coils to suppress absorber arcs. As a result, 300 kA of start-up current has been produced using just 27 kJ of stored capacitor bank energy. For the first time in NSTX, significant additional current has been generated when CHI-started discharges are coupled to induction. The electron temperature during the CHI phase of the discharge has reached 50 eV. Furthermore, the CHI-produced toroidal current that is available to be coupled to induction continues to increase with the delivered CHI capacitor bank energy at otherwise similar values of the injector flux. CHI in NSTX is energetically quite efficient, producing a plasma current of about 10 A/J of capacitor bank energy. These results demonstrate the high efficiency of CHI and its potential for substantial current generation in NSTX and future toroidal devices.

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