Ramp-Up of CHI-Initiated Plasmas on NSTX

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***Abstract*—Ongoing experiments on the National Spherical Torus Experiment have demonstrated ohmic transformer flux savings by initiating the discharge with transient coaxial helicity injection (CHI). The combined use of discharge cleaning of the CHI electrodes and use of lithium evaporation, along with the use of poloidal field coils, to produce a buffer flux that prevents arcs at the top of the device has been shown to reduce the radiation from low-Z impurities. Without such impurity reduction, CHI-initiated discharges could not have their plasma current increased by ohmic ramp-up; however, the CHI-initiated discharges with reduced low-Z radiation can be ramped up by induction and exhibit higher plasma current than discharges without the benefit of CHI initiation.**

***Index Terms*—Coaxial helicity injection (CHI), current drive, spherical torus (ST), start-up.**

I. INTRODUCTION

THE LOW ASPECT ratio, plasma major-to-minor-radius ratio, of the spherical torus (ST) [1] concept leads to advantages such as a high ratio of plasma pressure to toroidal field pressure (β) and a high bootstrap current fraction. The low aspect ratio means that there is little space to accommodate neutron shielding for a central solenoid in the next generation of STs and makes it highly desirable that the central solenoid be replaced by other means of start-up and current drive [2]. The National Spherical Torus Experiment (NSTX) is studying the use of coaxial helicity injection (CHI) [3], [4] to produce the initial plasma with sufficient plasma current to be the target for other noninductive means to ramp up the current.

The Helicity Injected Torus I [5] and II [6] (HIT-I and HIT-II) experiments employed CHI to form and sustain plasmas through nonaxisymmetric magnetic reconnection and relaxation processes. The earliest CHI experiments [7] on NSTX attempted to replicate these experiments by employing a rectifier power supply to provide the voltage across the CHI gap. Up to 400 kA of toroidal current was produced for hundreds of microseconds by this technique, but the resistive decay timescale of these discharges was much less than the discharge duration. These discharges generally ended with arcs before the planned termination, and the input power of up to 30 MW exceeded the power-handling capability of the divertor strike plates where most of the power was dissipated. A technique called transient CHI [8] was developed on HIT-II and applied to NSTX [9] to overcome these difficulties. In this technique, the duration of the applied voltage is kept short, typically less than about 4 ms, to minimize the plasma-facing-surface issues such as heating and impurity generation. Fig. 1 shows a cross-sectional schematic of NSTX with details relevant to CHI.

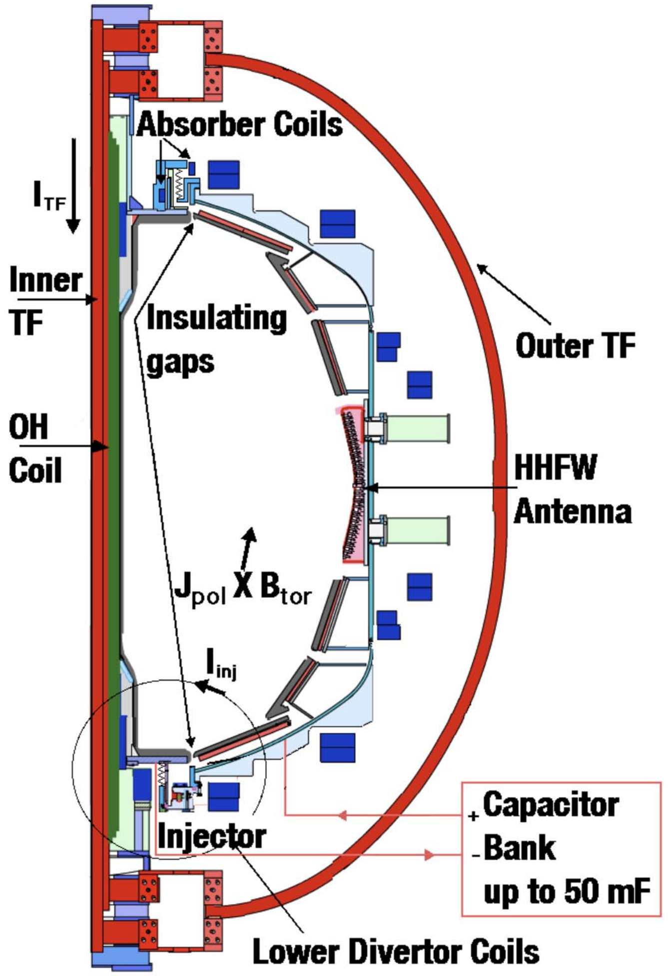

Fig. 1. This cross-sectional view of NSTX shows the field direction for the initial magnetization state of a transient CHI discharge. Gas is introduced into the volume below the injector gap (lower divertor gap) when the capacitor bank is fired.

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II. TRANSIENT CHI

The vacuum vessel in NSTX is electrically separated into inner and outer sections by insulating breaks at the top and bottom of the machine so that the inner and outer divertor regions are electrically isolated. CHI discharges are set up as follows: The initial toroidal field and poloidal field are applied so that the inner and outer divertors at the bottom of NSTX are connected by a helical field pattern, while the poloidal field connecting the inner and outer divertors at the top is minimized. The CHI discharges are initiated by applying a voltage of one to a few kilovolts across the insulated divertor gap and by simultaneously introducing a gas puff into the region below the lower divertor gap, also called the injector region. This causes plasma to form in the injector region. This helical electrode discharge can have toroidal plasma current $(I_{\rm tor})$ that is many times the injector current $(I_{\rm inj})$ across the gap. For NSTX, $I_{\rm tor}/I_{\rm inj}$ between 10 and 100 is typical. The toroidal field direction is chosen such that the $J_{\rm pol} \times B_{\rm tor}$ force on the plasma is up into the vacuum vessel.

There are several requirements to make transient CHI work: First, there must be enough energy in the voltage supply to provide sufficient $I_{\rm inj}$ to overcome the field line tension and exceed the "bubble burst" condition $I_{\rm inj} = 2\psi_{\rm inj}^2/(\mu_o^2 d^2 I_{\rm TF})$, where $I_{\rm TF}$ is the total toroidal field current through the center of the torus, d is the width of the injector flux footprint on the electrodes, which is the minimum distance between the points where the poloidal field linking the CHI electrodes penetrates them, and $\psi_{\rm inj}$ is the poloidal flux linking the injector insulating gap [10].

Second, the CHI discharge must fill the vessel quickly to keep the required duration of $V_{\rm inj}$ short. This is dependent upon the applied $V_{\rm inj}$ since this determines the rate at which toroidal flux (ϕ_T) crosses the injector and absorber gaps: $V_{\rm inj} = {\rm d}\phi_T/{\rm d}t$. In NSTX with $B_T = 0.3$ T on axis, $\phi_T \sim 1.4$ Wb inside the vessel. For 2 kV, the time needed to replace all ϕ_T's within the vacuum vessel is about 0.7 ms. This pulse duration is easily supplied by the capacitor bank for NSTX.

Third, the energy stored in the capacitor bank must be enough to fully ionize and heat the injected gas. It requires about 50 eV to ionize each atom and an additional 60 eV to heat each ion to 20 eV [11]. In order to reduce the quantity of gas required to initiate CHI to approximately that used to fuel an ohmic discharge, it was necessary to move the CHI gas injection port from the main chamber to the small enclosed volume ($\sim$100 L) below the lower divertor gap. For the total gas needed to achieve breakdown in NSTX, the energy needed to ionize and heat the gas is a few kilojoules, much less than that available from the NSTX CHI capacitor bank.

Fourth, the capacitor must be able to supply the magnetic energy due to the toroidal plasma current, $1/2L_pI_p^2$, where L_p is the inductance of the plasma. Since $E_{\rm cap} = 1/2CV^2$ and the inductance of typical NSTX plasmas with closed flux surfaces is about 0.5 μH, this limits I_p to about 500 kA with the present capacitor bank.

Fifth, the flux footprint of the initial CHI plasma must be narrow enough to make the distance over which reconnection needs to occur small, but large enough to be consistent with meeting the "bubble burst" condition.

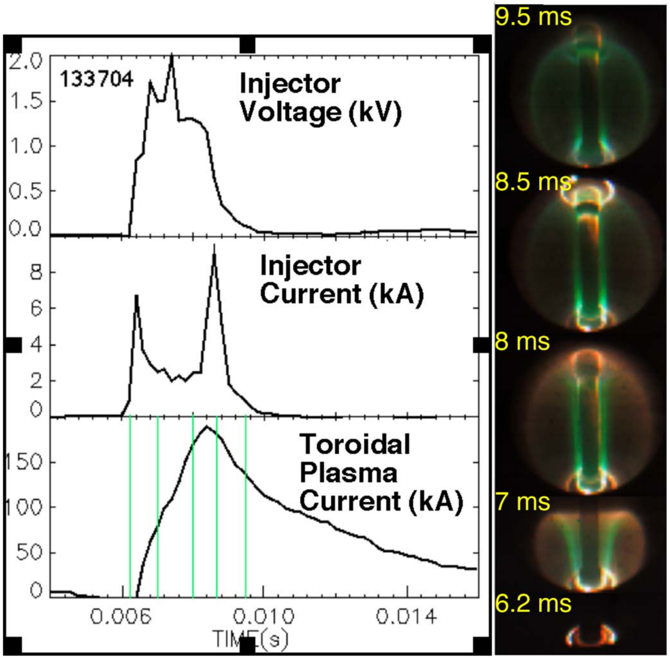

Fig. 2. (Left) CHI injector voltage and current and the plasma current versus time for a CHI-only discharge. (Right) Fast color camera images of the plasma taken at the times marked by the green bars in the left figure as it grows up from the bottom after breakdown at about 6 ms. Note that the ratio of $I_{\rm inj}/I_{\rm ptor}$ reaches well over 50 before an absorber arc occurs at about 8.5 ms.

Finally, applying high voltage to the vacuum vessel raises the possibility of both internal arcs across the insulators and external arcs from the vessel to ground. Because the plasma represents a variable load to the injector voltage, large voltage spikes well in excess of that applied can be produced. For NSTX, with the use of only 1 kV on the CHI electrodes, voltage spikes >3 kV were measured, which sometimes resulted in external arcs. In order to reduce these voltage spikes, analysis indicated that transient suppression was required. Transient suppression on the microsecond timescale was accomplished by use of a capacitive snubber circuit that is close to the vacuum vessel connected by low-inductance leads. Suppression on longer timescales is provided by metal–oxide varistors connected in 4 parallel groups of 160 parallel modules [12].

In the CHI discharge shown in Fig. 2, 1.65 kV was applied across the injector gap using 10 mF in the capacitor bank. The discharge was initiated at 6 ms; 2.5 ms later, a crowbar circuit was used to short the capacitor bank and reduce $I_{\rm inj}$ quickly to zero. The fast camera images in Fig. 2 show the plasma as it grows in size and current to nearly 200 kA in only 2.5 ms. The image at 8.5 ms clearly shows a bright flash at the top divertor gap, also called the absorber gap, which is coincident with a rapid increase in $I_{\rm inj}$. Such flashes are referred to as absorber arcs since continued application of the CHI voltage results in a rapid discharge of the CHI capacitor's stored energy. The occurrence of these arcs is common, and while they seem rather benign to the CHI discharge if the voltage is removed quickly, they can provide a source of impurities that makes coupling to inductive ramp-up impossible. It is clear that these arcs must be avoided or their effects minimized if CHI is to be effective.

As I_{inj} falls to zero, I_{tor} is then current flowing on closed flux surfaces and is hereafter referred to as I_p. The measured I_p then decays with a time constant of approximately 5 ms which is less than that for an ohmic plasma due to the lower electron temperature of about 20 eV for CHI compared to a typical value of $\sim$200 eV at $I_p = 100$ kA.

III. EXPERIMENTAL RESULTS

Transient CHI on NSTX has successfully produced up to 160 kA of plasma current on closed flux surfaces [12]. Such CHI-produced plasmas can be ramped up in current to produce high-performance NSTX H-Mode plasmas [9]. While it is the ultimate goal to use a noninductive plasma current ramp-up scenario to increase the CHI-initiated current, at present, the only reliably proven technique to ramp I_p up is inductively with the use of the OH solenoid. It is important to demonstrate that the coupling of CHI-initiated discharges to a ramp-up technique is possible. In the process of this investigation, it was noticed that CHI discharges with relatively high levels of low-Z impurities, most notably oxygen, would not couple to inductive ramp-up effectively. In order to reduce these impurities, a three-pronged approach was used. 1) The duration of the CHI voltage application was shortened both to reduce the total energy striking the divertor plates and to reduce the incidence of arcs at the top of the machine which occur when a poloidal field from the plasma links the inner and outer vessels there. 2) A conditioning campaign was undertaken in which a rectifier power supply was used to provide about 1 kV for a 0.4-s-long CHI discharge formed using a sufficient poloidal flux to prevent the plasma from expanding fully into the vessel. Furthermore, the upper divertor region was conditioned by using beam-heated double-null discharges unbalanced slightly upward, something that is seldom done on NSTX. 3) Li evaporation was used to reduce impurities. The Li evaporator system is described and has been shown to lower the oxygen in normal NSTX discharges [13]. Fig. 3 shows two similar CHI discharges taken using 10 mF of capacitance. The discharge shown in blue was taken near the beginning of the CHI campaign and did not have Li evaporation. The discharge indicated in red was after the conditioning campaign described earlier, and Li was being evaporated at the rate of 12 mg/min between discharges. It is clear that the measured intensity of the OII light is much lower for the discharge after conditioning and with Li in both the upper and lower divertor regions. For both of these discharges, about 4 V/turn was being supplied by the ohmic transformer (OH); only the second had effective plasma current ramp-up after CHI. In fact, no discharges with relatively high levels of O-II emission were ramped up with the OH. In the past, we have reported that low-Z impurities increased with increasing capacitance (energy) in the CHI system and had been successful using only up to 5 mF to couple to induction [4]. At present, successful discharges with 15 mF have been achieved, although the success rate was much lower than that for discharges using 10 mF.

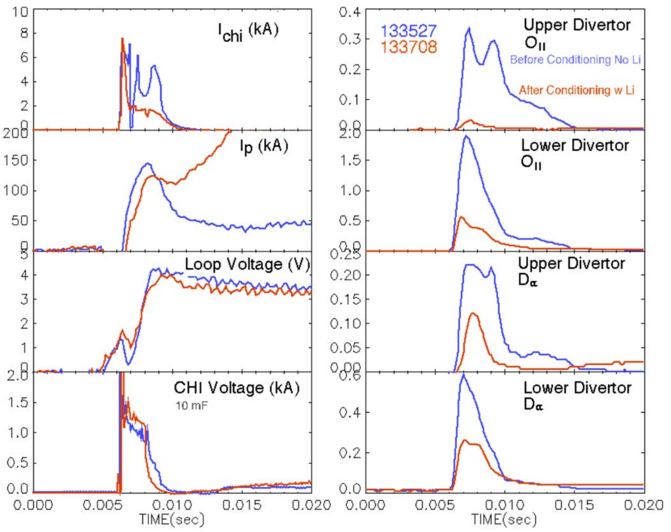

Fig. 3. Two CHI-initiated discharges. The discharges with the curves indicated in blue are from a discharge taken early in the CHI campaign, while those in red are from a discharge after discharge cleaning and with the benefits of Li evaporation.

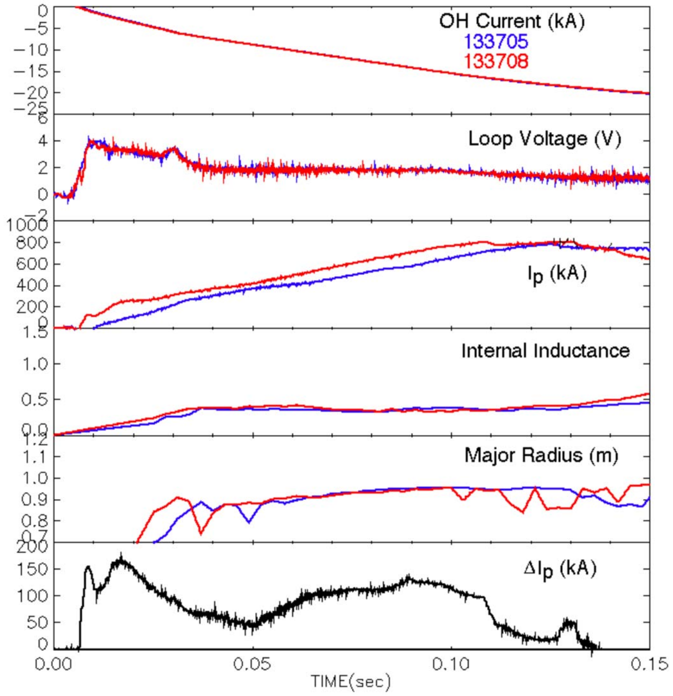

Fig. 4. Comparison of discharges taken with CHI coupled to inductive ramp-up in red and with induction only in blue. The discharges had identical OH current programming and thus similar loop voltage histories. The CHI plus ohmic clearly has higher current until a reconnection event occurs as the loop voltage is reduced. The similar internal inductance and major radius of the plasmas indicate that the increased plasma current shown in the bottom frame is due to real flux savings with CHI.

Comparison discharges were produced, one using the ohmic transformer to initiate and ramp up the plasma and another with CHI initiation and ohmic ramp-up. The OH current programming was identical for the two shots. As can be seen in Fig. 4, the plasma current is higher in the CHI-initiated discharge shown in red. The poloidal plasma flux defined as $\mu_0 l_i R_p I_p/2$ is also higher in the CHI shot. Magnetic equilibrium analysis with the EFIT code [14], [15], using Thomson scattering and the diamagnetic loop as constraints, indicates that the plasma internal inductance l_i and major radius R_p are similar in the two shots. The difference in I_p for the two shots is shown in the last frame in Fig. 4. The CHI shot is 50–170 kA higher than the OH-only shot, until a reconnection event occurs after 0.1 s. This represents ohmic flux savings with CHI initiation and also demonstrates that CHI can produce plasmas that are capable of being ramped up by another technique. It should be noted that the uncertainty in the equilibrium analysis for plasmas with I_p less than about 300 kA is large due to the presence of comparable vessel currents. As I_p increases and the loop voltage V_{loop} is reduced, this uncertainty falls to typical values from the EFIT analysis, when the uncertainties are less than 0.01 m ($\sim$1%) for R_p and less than 5% for l_i.

IV. CONCLUSION AND FUTURE WORK

In order to increase the plasma current driven by CHI and coupled to induction, it is necessary to increase the capacitance used in the CHI system, and the low-Z impurities must be simultaneously controlled. This can be accomplished in a variety of ways: further conditioning the electrodes, suppressing the formation of arcing in the upper divertor region by use of coils installed for that purpose, increasing the amount of Li evaporation, or using a metal as the divertor plates in NSTX. The first three of these techniques will be implemented in the remainder of the 2009 run, while the use of partial metal divertor plates will occur after the installation of the liquid Li divertor tray in the fall of 2009. The scaling of transient CHI with capacitor bank energy and the results from the 10-mF bank used in the present experiment indicate that the existing 50-mF capacitance available on NSTX is sufficient to produce $I_p > 500$ kA if the influx of low-Z impurities can be reduced at a higher CHI discharge energy.

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