

Coupling of Coaxial Helicity Injection plasma start-up to inductive ramp-up on the National Spherical Torus Experiment*

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INTRODUCTION

The low aspect ratio (plasma major to minor radius ratio) of the spherical torus (ST)[1] leads to advantages such as a β , which means more efficient use of the toroidal magnetic field, and a high bootstrap current fraction, which reduces the externally generated current needed to sustain the discharge. These advantages of the ST have the potential to make it a more efficient fusion reactor. However, the low aspect ratio means that there is not enough space to accommodate a central solenoid in a reactor making it essential to develop other means of current drive. Experiments on the National Spherical Torus (NSTX) have now demonstrated a reduction in the solenoid flux required for plasma startup using transient coaxial helicity injection (CHI), a method previously developed on the Helicity Injected Torus-II (HIT-II).[2] The NSTX results represent a proof-of-principle test on a machine 30 times larger in volume than HIT-II. The combination of the NSTX and HIT-II results also show that the method scales favorably as the ST size is increased. A goal of CHI research on NSTX is to produce an initial plasma with sufficient toroidal current to provide a target that allows other forms of current drive to ramp-up and maintain the plasma current (I_p).

CHI discharges with up to 0.3 MA of toroidal plasma current have been ramped up inductively and reach higher final current than discharges without the benefit of CHI initiation. This demonstrates that the CHI produced plasmas are compatible with normal tokamak operation and represents an important step towards a solenoid-free ST.

TRANSIENT CHI

The NSTX stainless-steel vacuum vessel (major radius 0.85 m) is electrically separated into inner and outer sections by toroidal ceramic insulators at the top and bottom of the center column such that the inner divertor is isolated from the outer divertor. The plasma facing components (PFCs), including the divertor plates, are covered with graphite tiles. Refs. [3] and [4] describe the NSTX device in more detail and present recent experimental results respectively.

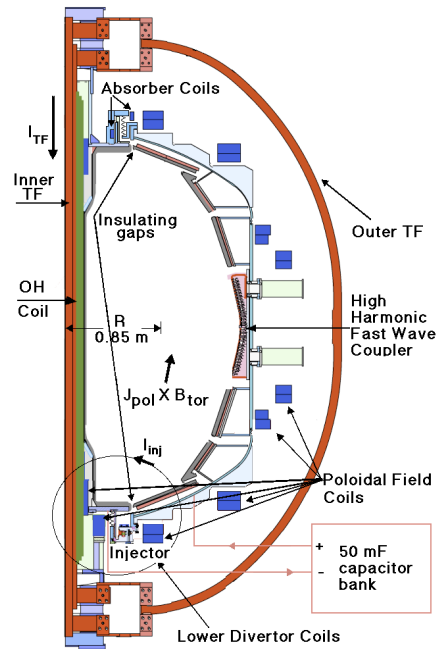


Figure 1. Cross-sectional view of NSTX showing the elements important to CHI initiation. The lower divertor is the injector and the upper divertor region is referred to as the absorber.

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CHI discharges are initiated by providing toroidal field and an initial poloidal field that connects the inner and outer divertors as shown schematically in Fig. 1. Gas is injected into and voltage is applied across the toroidal gap between the inner and outer lower divertor plates which we call the injector (the insulating gap at the top we refer to as the absorber). A discharge forms across the injector gap with current flowing from the outer to the inner lower divertor plates. The injected current initially follows the applied field so the toroidal plasma current I_p is many times the poloidal current.

The first CHI experiments on NSTX [5] attempted to reproduce the results observed on HIT-I [6] and HIT-II [7] where non-axisymmetric magnetic reconnection and relaxation were employed to transfer the CHI current from open to closed magnetic surfaces. The early NSTX experiments used programmable rectifier power supplies to supply the injector voltage between the inner and outer vessel sections. Up to 400 kA of toroidal current was produced in these “steady-state” CHI discharges in NSTX where the resistive decay time scale of the plasma was much less than the discharge duration. However, there was little evidence that the plasma formed on closed field lines; the discharges generally terminated early due to an absorber arc, a condition when a second discharge forms across the insulator in the upper divertor region and provides an alternate path for the injected current. Subsequently, a new technique, called transient CHI [8], was developed on HIT-II and implemented on NSTX [9], to provide a plasma suitable for I_p sustainment or ramp-up by other means.

To produce transient CHI discharges on NSTX, a capacitor bank of up to 50 mF charged up to 1.75 kV is connected to the injector by an ignitron switch, with the outer vessel acting as the anode. As the injector current (I_{inj}) linking the inner and outer divertors increases, the $J_{pol} \times B_T$ force overcomes the field line tension and the plasma expands into the main chamber as shown in the fast camera frames in Fig. 2, until it fills the torus volume. After a pre-programmed time (typically 2.5 to 5 ms) near the peak in the toroidal current, the capacitor bank is diverted into a low resistance by a second

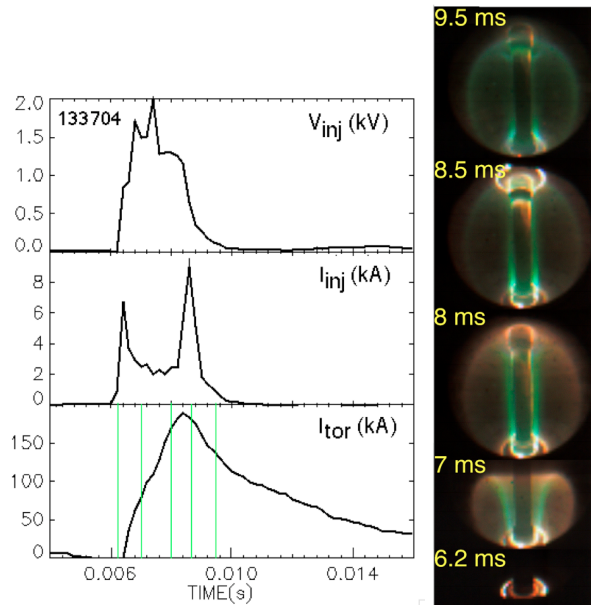


Figure 2. On the left are shown the injector voltage and current and the plasma current for a CHI discharge. On the right are fast color camera images of the plasma taken at the times marked by the green bars in the left figure as it grows from the injector after breakdown at about 6 ms. The ratio of I_{inj}/I_{ptor} reaches well over 50 before an absorber arc occurs at about 8.5 ms.

ignitron. As the injector current falls, the plasma detaches from the electrodes to form closed flux surfaces. The top frame in Fig. 2 shows the plasma after I_{inj} is reduced to zero, when the toroidal current (I_p) of up to 160 kA forms closed flux surfaces and decays resistively to zero with a decay time constant of approximately 5 ms. Since there is no current flowing across the divertor gap while the toroidal plasma current persists for several ms, it is clear that the plasma current is flowing on closed field lines. These results represent a world record non-inductive start-up current of 160 kA on closed flux surfaces in a toroidal magnetic configuration [10]. Such CHI produced plasmas can be ramped up in current to produce high performance NSTX neutral-beam-heated H-Mode plasmas.[10]

COUPLING CHI INITIATION TO INDUCTIVE RAMP-UP

Although an ultimate goal of this research is to use non-inductive current drive to increase the CHI initiated current, at present the most reliable technique to ramp I_p on NSTX is inductively using its central solenoid. In the course of these experiments, it was found that CHI discharges with relatively high levels of low Z impurities, most notably oxygen, would not couple to inductive ramp-up

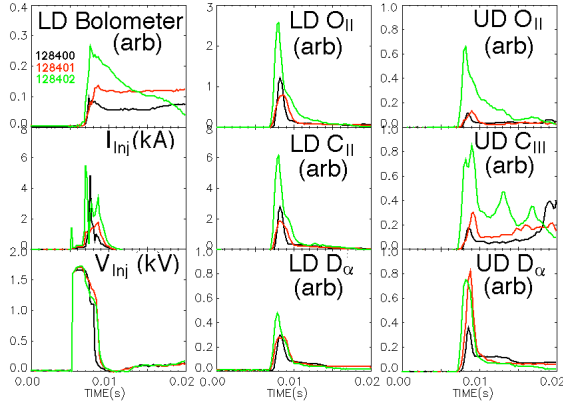


Figure 3. Discharges using 5 (black), 10 (red) and 15 mF (green) capacitance at 1.7 kV for the CHI. The increased CHI energy results in higher impurity levels in both the lower (LD) and upper divertor (UD) as well as increased radiated power in the lower divertor.

up effectively. Figure 3 shows three discharges with 5, 10 and 15 mF in the CHI capacitor, each charged to 1.7 kV. The low-Z impurity radiation in both the upper and lower divertor regions increased as the CHI energy was increased. In each of these discharges, an inductive loop voltage of 3.6 V/turn was applied. The plasma current achieved at 40 ms was similar for the 5 and 10 mF cases, but zero for 15 mF which had the highest low-Z impurities. In order to reduce these impurities, a four pronged approach was used. (1) The duration of the CHI voltage was shortened both to reduce the total energy striking the divertor plates and to avoid arcs at the absorber gap

which occur when poloidal flux generated by the plasma links the inner and outer vessel there. (2) The injector electrodes were conditioned by using a rectifier power supply to produce a 0.4 s long CHI discharge while sufficient poloidal flux was applied to prevent the plasma from expanding out of the injector. In addition, the upper divertor region was conditioned by using NBI-heated double-null divertor discharges unbalanced slightly upward. (3) Lithium (Li) evaporation onto the graphite PFCs was used to reduce impurities. The evaporator system, described in Ref. 11, has been shown to lower the oxygen in normal NSTX discharges.[11] (4) Small poloidal field coils located near the upper insulator, known as the absorber coils (Fig.1), were energized to provide a buffer flux to slow the growth of the plasma towards the absorber gap and avoid arcs there.

Two similar discharges taken using 10 mF capacitance are shown in Fig. 4. The discharge in blue did not have Li evaporation, while the discharge indicated in red was after the conditioning campaign and received Li evaporation. The intensity of the OII light is lower for the discharge after conditioning and with Li in both the upper and lower divertor regions. For these discharges, about 3.5 V/turn was applied by the ohmic transformer. Only the discharge that benefitted from conditioning had effective plasma current ramp-up after

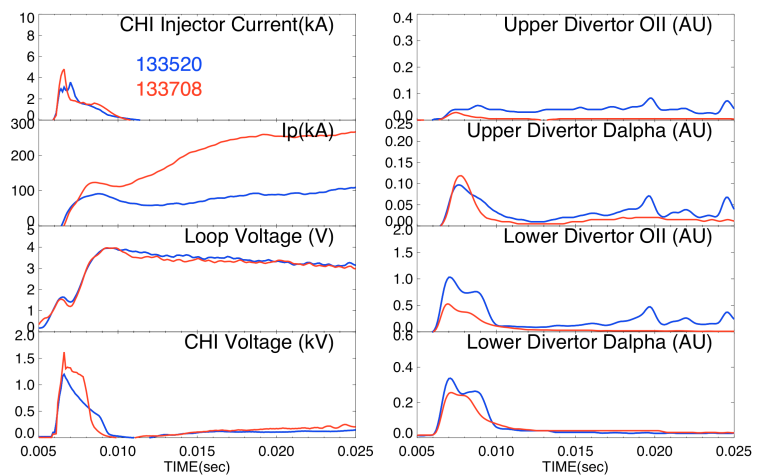


Figure 4. The CHI discharge indicated in blue was taken early in the CHI campaign, while the one in red was benefited from discharge cleaning Li evaporation. Both CHI discharges used 10 mF at 1.7 kV.

CHI. No discharges with high levels of O-II emission were successfully ramped up with induction. In the past, the low Z impurities increased with the CHI energy and successful coupling to induction was then rarely achieved when using more than 5 mF [4].

A comparison of the plasma current and impurity influx for CHI initiated discharges using 5, 10, 15 and 20 mF with a purely inductive discharge without CHI is shown in Fig. 5. The discharges using up to 15 mF reached currents above the purely inductive case, which increased with increasing capacitance. However, although the absorber coils were used, in the 20 mF case, an absorber arc occurred that increased the low-Z impurities and limited I_p . Although successful discharges have been achieved using 20 mF, the success rate was much lower than for discharges using 10 mF.

Two discharges with identical solenoid current, one with and one without CHI initiation, have been analyzed with the EFIT code[12,13], using Thomson scattering data for $T_e(R)$, $n_e(R)$ and the diamagnetic loop as constraints. The CHI initiated discharge had about 110 kA more plasma current and 30 mWb more internal poloidal flux defined as $\mu_0 I_p R_p / 2$ at 0.1 s. However, it should be noted that the uncertainty in the equilibrium analysis for plasmas with low current and high loop voltage is significant due to the presence of large currents in the vacuum vessel.

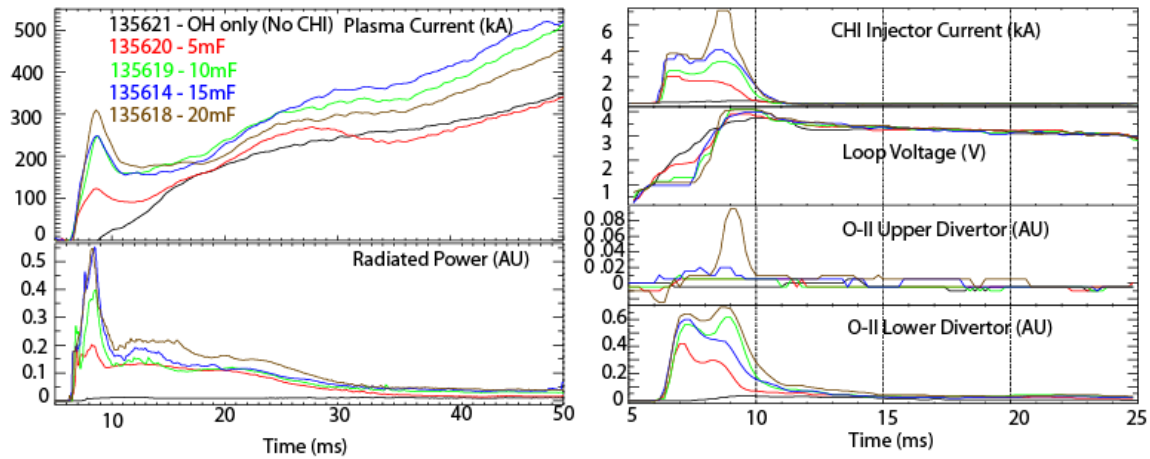


Figure 5. Five discharges with inductive ramp-up using the same applied loop voltage and coil currents up to 40 ms. The black curves are from a purely inductive discharge while the red, green, blue and brown indicate CHI initiated discharges using 5, 10, 15 and 20 mF respectively.

The results from the present experiments and the scaling of CHI current with capacitor bank energy suggest that the existing system on NSTX should be sufficient to produce $I_p > 500$ kA if the influx of low-Z impurities can be reduced at the higher CHI discharge energy.

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