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Coaxial Helicity Injection plasma start-up coupled to inductively driven sustainment on the National Spherical Torus Experiment*

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INTRODUCTION

The spherical torus (ST)[1] concept has advantages as a result of its low ratio of plasma major radius to minor radius, which allows a high ratio of plasma pressure to toroidal field pressure (β) and a high fraction of bootstrap current. As a result of this low-aspect ratio, plasma current start-up and current sustainment are challenging issues for the next generation of spherical tokamaks (ST). The small bore in the ST design permits little or no room for inclusion of a conventional central solenoid to provide inductive current drive, so it is essential that alternative techniques to start, ramp-up and sustain plasma current be demonstrated for the ST

The National Spherical Torus Experiment (NSTX) is investigating the use of coaxial helicity injection (CHI)[2] as a method to produce the initial plasma and sufficient toroidal current to provide a target that allows other forms of non-inductive current drive to ramp-up and maintain the toroidal plasma current. Transient CHI was first demonstrated on the Helicity Injected Torus-II (HIT-II)[3] where the CHI produced plasma current also was increased and sustained by induction. On the much larger National Spherical Torus Experiment (NSTX), plasmas with higher initial CHI-driven current have been increased and sustained using inductive current drive with flux supplied by the central solenoid. This demonstrates that the CHI produced plasmas are compatible with normal tokamak operation and represents an important step in the path towards a solenoid-free ST design.

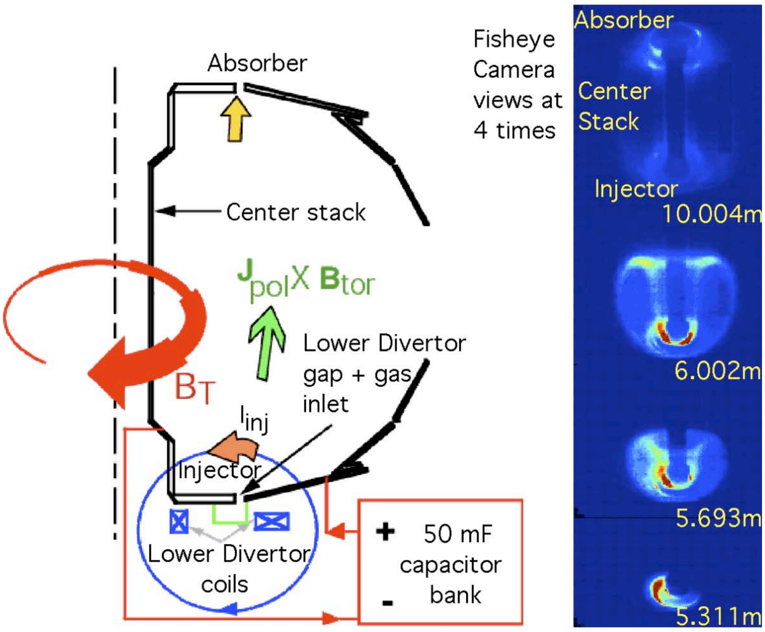

Fig. 1. The schematic diagram shows the CHI start-up configuration on the left. On the right are shown fast TV images of the plasma evolution. Notes: the first light in the injector region was visible after 5.15 ms and the image from 10.004 ms is after the injector current returned to zero.

The NSTX stainless-steel vacuum vessel (major radius 0.85 m) is electrically separated into inner and outer sections by means of toroidal ceramic rings at the top and bottom of the center column such that the inner divertor is isolated from the outer diverter. The plasma facing surfaces that are close to the plasma, including the divertor plates, are covered with graphite tiles. Refs. [4] and [5] describe the NSTX device in more detail and present recent experimental results respectively.

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 introduced into the volume below the lower divertor gap and voltage (1 to 2 kV) is applied across the gap. A discharge forms with current flowing from the outer to the inner divertor plates. The injected current essentially follows the helical field lines so the toroidal current is many times the poloidal current. When the discharge first forms, the plasma is near the divertor gap, which we call the injector. The gap at the top of the machine is referred to as the absorber.

TRANSIENT CHI

The first CHI experiments on NSTX[6] attempted to reproduce the results observed on HIT-I[7] and HIT-II[8] wherein 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 (V_{inj}) 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 arcs. The high power (up to 30 MW) used to drive the CHI discharge was not compatible with the power handling capability of the plasma facing compoents for long times. Instead a new technique, called transient CHI[9], was developed on HIT-II and implemented on NSTX[10], to provide a plasma suitable for I_p sustainment or ramp-up by other means.

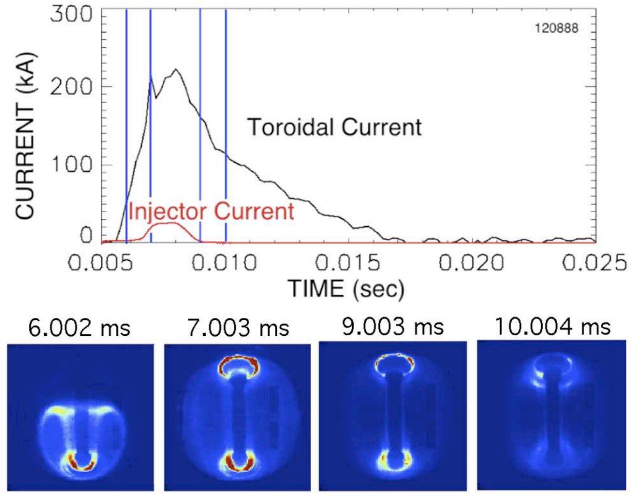

Fig. 2. The injector current returns to zero at 9 ms when the toroidal current is 160 kA. The 4 vertical lines in the top of the figure indicate the times of the 4 fast camera images from the same shot which are shown in the lower portion of the figure.

The procedure to produce transient CHI discharges on NSTX is as follows. The toroidal field current is ramped up to its desired value and the initial vacuum poloidal flux is established. A pre-programmed amount of deuterium, comparable to that used for normal inductive start-up, is then injected and the microwave pre-ionization is applied in the volume below the lower divertor gap. The capacitor bank up to 50 mF pre-charged up to 1.75 kV is connected to the inner and outer vessel by an ignitron switch with the outer vessel acting as the anode to form a discharge, typically at 5 ms. After a pre-programmed time (typically 3 to 5 ms) chosen to allow the plasma to expand into the vessel volume and at a time near the peak in the toroidal current, the capacitor bank is shorted into a low resistance by a second ignitron. 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. As the injector current falls rapidly to zero, 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 demonstration of a world record non-inductive start-up current of 160 kA on closed flux surfaces in a toroidal magnetic configuration.

COUPLING TO OH SUSTAINMENT

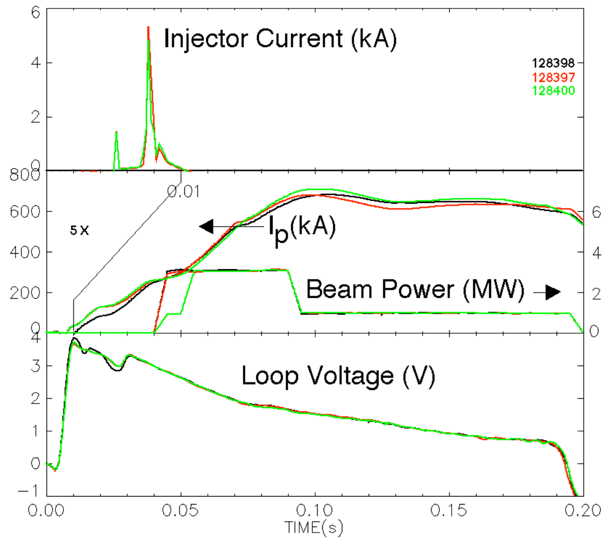

Fig. 3. Comparison of CHI initiated plasma (green and red curves) with an Ohmic initiated plasma (black curves). Note the expanded time in the top frame. All discharges used the same Ohmic coil current programming.

The central solenoid has been usedin order to provide current drive to sustain and increase the current in CHI initiated discharges on NSTX. Fig. 3 compares discharges initiated with and without CHI and ramped up to over 600 kA using the same transformer current programming and neutral beam injection heating. CHI initiated discharges can transition into H-Mode, reach electron temperatures of 800 eV and have low inductance, preferred for high-performance NSTX discharges. Fig. 4 shows the electron density (n_e), electron temperature (T_e) and ion temperature (T_i) profiles for a CHI-initiated, neutral-beam-heated discharge after the transition into H-mode. However, the CHI discharges did not show increased I_p with the same flux like that seen on HIT-II.[9] The lack of flux savings is probably due to an influx of impurities with the CHI initiation. Earlier attempts to add the ohmic drive to CHI initiated discharge resulted in no increase in I_p, but there was a significant increase in the O-II emission. It was not until further conditioning was performed in the form of D_2 glow discharge cleaning (GDC) and electrode discharge conditioning that the plasma current was increased by induction. Further evidence for the need to condition the walls and/or divertor plates is shown in Fig. 5. Shots taken with 1, 2, and 3 capacitors in the CHI system differed primarily in the intensity of the low Z impurity emission and increased

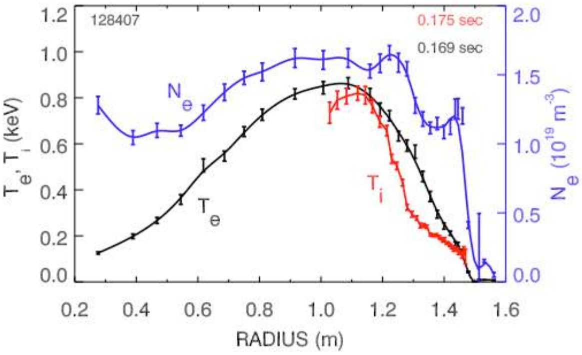

Fig. 4. Electron and ion temperature and electron density profiles (T_e, T_i, n_e) after transition to H-Mode in a discharge initiated with 2 capacitor banks in the CHI system and heated with 4MW of neutral beam power.

radiation measured by a bolometer viewing the injector region with only modest changes in the plasma current. The need for excellent vacuum conditions in order to successfully couple the CHI discharge to Ohmic drive was also found on HIT-II.

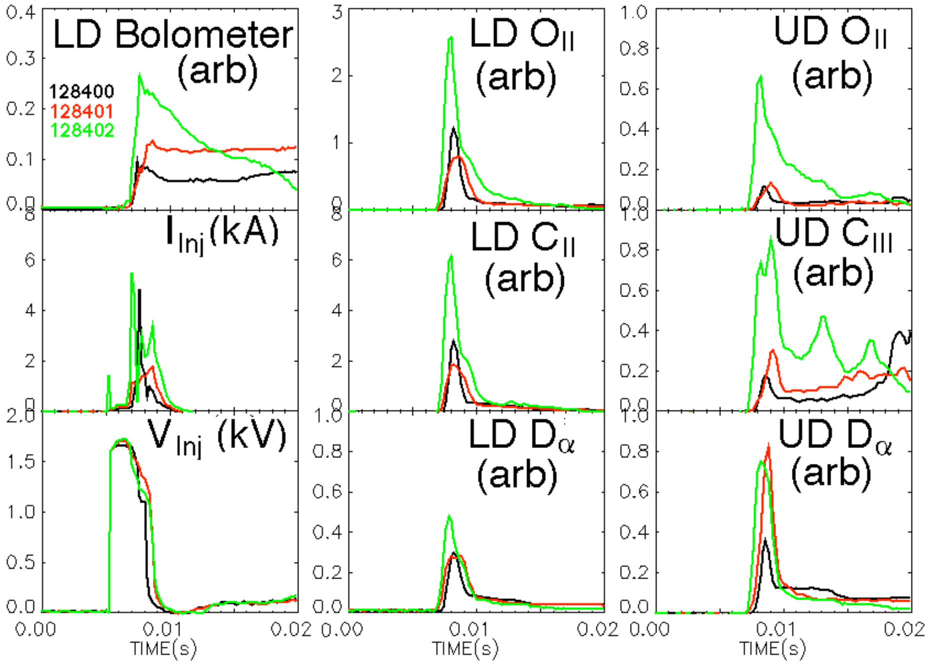

Fig.5. Discharges using one (black), two (red) and three (green) capacitors in the CHI system. Note that the increased energy used by the CHI results in higher impurity levels in both the lower (LD) and upper divertor (UD) as well as increased radiated power in the lower divertor.

SUMMARY

Using the method of transient CHI, world-record non-inductive start-up plasma current flowing on closed field lines in a toroidal confinement device of 160 kA has been unambiguously achieved. The resulting plasmas have electron temperatures of about 20 eV and decay resistively in several ms. Planned future experiments will include studying the effect of Li conditioning to reduce low Z impurities and its impact on the ability to demonstrate flux savings with CHI start-up.

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