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Coaxial Helicity Injection for plasma start-up in NSTX

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Abstract.

Coaxial Helicity Injection (CHI) on the National Spherical Torus Experiment (NSTX) has produced 390*kA* of toroidal current without the use of the central solenoid. The ratio of the toroidal current to the injector current has reached 14. CHI discharge pulse lengths of up to 330*ms* were obtained.

1. Introduction

The Spherical Torus is a magnetic confinement concept that has the advantages of high beta and a projected high fraction of bootstrap current drive. The favorable properties of the ST arise from its very small aspect ratio which leaves very restricted space for a central solenoid to induce the toroidal current. This makes sustained non-inductive operation necessary for the success of the ST concept. Coaxial Helicity Injection is a promising candidate for initial plasma generation and for edge current drive during the sustained phase. CHI is implemented on NSTX by driving current along field lines that connect the inner and outer lower divertor plates. A 50*kA*, 1*kV* DC power supply is connected across the inner and outer vessel components which are insulated from each other by ceramic rings at the bottom and top. CHI on NSTX draws on extensive experience from the smaller HIT and HIT-II experiments at the University of Washington [1,2]. A description of the CHI system on NSTX can be found in Reference [3].

The CHI method drives current initially on open field lines creating a current density profile that is hollow and intrinsically unstable. Taylor relaxation 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. Such current penetration to the interior is eventually needed for usefully coupling CHI to other current drive methods and to provide CHI sustainment current during the long pulse non-inductive phase.

2. Experimental results

Figure 1 shows the injector current; toroidal current, the applied injector voltage, the injector flux, and the current in the lower divertor coil (labeled PF3L), for a CHI produced discharge. The applied CHI injector voltage determines the amount of injector current that can be driven for each combination of toroidal field, injector flux and gas pressure. The injector flux is defined as the difference in poloidal flux between the upper and lower insulating gaps separating the inner and outer electrodes. In this discharge, as the injector voltage is increased and the injector flux reduced, the toroidal current reaches nearly $400kA$. The corresponding injector current is $28kA$, which results in a current multiplication factor of 14, the highest yet measured for a CHI discharge. The measured current multiplication is roughly equal to the ratio of the toroidal flux within the discharge region to the injector poloidal flux, which is the theoretical maximum attainable. For $t < 200ms$, the toroidal current trace is smooth. During the subsequent high current phase, there is pronounced oscillation in the toroidal current signal and the amplitude of voltage fluctuations increases. Fast camera images of the discharge show large-scale vertical motion of the CHI plasma. It is not known at this time if these are evidence of large scale reconnection events that lead to closed flux plasma which then decays, only to be re-established. Active control of these plasmas is needed before a CHI discharge can be adequately characterized or auxiliary heating and current drive can be applied. A magnetic perturbation with amplitude $2mT$ measured at the outboard midplane and toroidal mode number $n=1$ is observed, rotating toroidally in the $E_r \times B_p$ direction with a frequency in the range $5 - 12kHz$. Such a mode, which has been found to be necessary for flux closure in HIT-II, may be a signature of magnetic reconnection to closed flux surfaces. The soft x-ray emission, measured by an array of detectors sensitive above about $100eV$, continues to increase as the toroidal current increases. The emission is seen mostly on the inboard side of the discharge probably because the current density is higher there. Measurements of the carbon line emission along a chord passing through the center of the plasma on the midplane indicate an ion temperature of about $30eV$ and a toroidal rotation velocity consistent with the magnetic measurements.

The poloidal flux during the discharge has been calculated by the magnetic fitting code MFIT [4] which distributes currents on a hypothetical set of toroidal filaments to match external magnetic measurements. During the high current portion of the discharge, the inferred poloidal flux contours in the lower divertor region are close together and resemble those for a lower single-null divertor discharge. We refer to this as the "narrow" footprint case, a condition that is believed to facilitate flux closure. In previous experiments, high currents could be attained only in the "wide" footprint condition when the flux contours are farther apart. The calculated changes in the flux contours during the discharge are shown in Figure 3. Note that while these MFIT results are consistent with flux closure, MFIT cannot prove closure *per se* since its analysis is based on external measurement only. The PF3L coil

is used to transition from the "wide" to the "narrow" case. Reversing the current in the PF3L coil causes the lower flux footprints to be squeezed closer. After current reversal, the current in this coil is opposite in direction to the toroidal current, causing the CHI plasma discharge to be pushed away from this coil. A compensating increase in the current in the upper PF3U coil is then needed for plasma equilibrium in the vertical direction. This however increases the magnetic field in the absorber region (the region near the insulating gap at the top of the machine), thereby increasing the likelihood of an absorber arc, a condition in which the insulator becomes electrically shorted by a localized discharge. In CHI discharges prior to June 2001, reversing the current in the PF3L coil always resulted in absorber arcs, but in more recent cases the arcs have been suppressed by careful programming of the other coil currents. The impedance of a CHI discharge, for similar other conditions, is approximately linearly proportional the toroidal field, probably because the length of a field line length joining the injector electrodes becomes proportionally longer. Increasing the toroidal field from 0.3 to $0.4T$ required an increase in the injector voltage from 0.8 to $1kV$, the voltage maximum, while the injector current reduced to $25kA$. Extension of CHI discharges to higher toroidal field operation will likely require higher voltage capability.

Experiments to date have shown that CHI engineering systems can be applied to a large ST for the production of substantial toroidal current. Our plans on NSTX are to produce higher current, longer discharges for characterization with and without auxiliary heating. To this end, we will modify the absorber region to suppress arcs and implement feedback of the CHI discharge. Absorber modifications will allow for the implementation of both an absorber feedback control system (based on the HIT-II system) to reduce unwanted magnetic fields in the absorber and an equilibrium feedback control system, (based on the present NSTX flux expansion method) to predict and correct the boundary flux. Feedback control of NSTX discharges should allow improved control of the discharge and help to retain the large amount of closed flux that is expected from future higher current CHI discharges in NSTX.

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References:

[1] T.R. Jarboe et al, "Current Drive Experiments on the HIT-II Spherical Torus," *17th IAEA Fusion Energy Conference*, Yokohama, IAEA-CN 69/PDP/02 (1998).

[2] B.A. Nelson et al., "CHI Current Drive on the NSTX and HIT-II Spherical Tori," *28th EPS Conference on Controlled Fusion Research*, Madeira, Portugal 18-22 June (2001).

[3] R. Raman et al., *Nucl. Fusion* **41**, 1081 (2001).

[4] L. Lao et al., *Nucl. Fusion*, **25**, 1611 (1985). M. Schaffer (private communication).

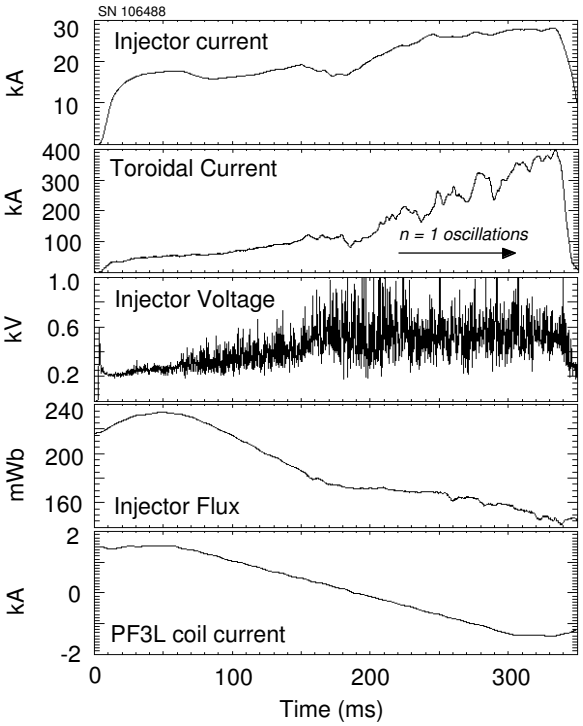


Figure 1 (above): High current CHI discharge on NSTX.

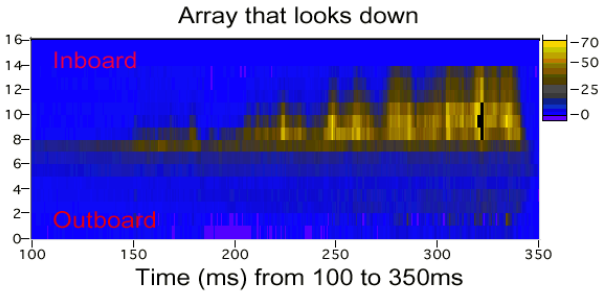
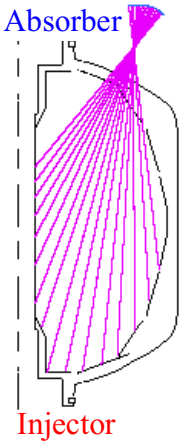


Figure 2 (above and right): Intensity contours of soft x-ray emission (Eγ > 100eV) on a fan of detectors (shown at right). The emission comes mostly from the inboard region near the midplane and not from the chords which pass through the injector region.



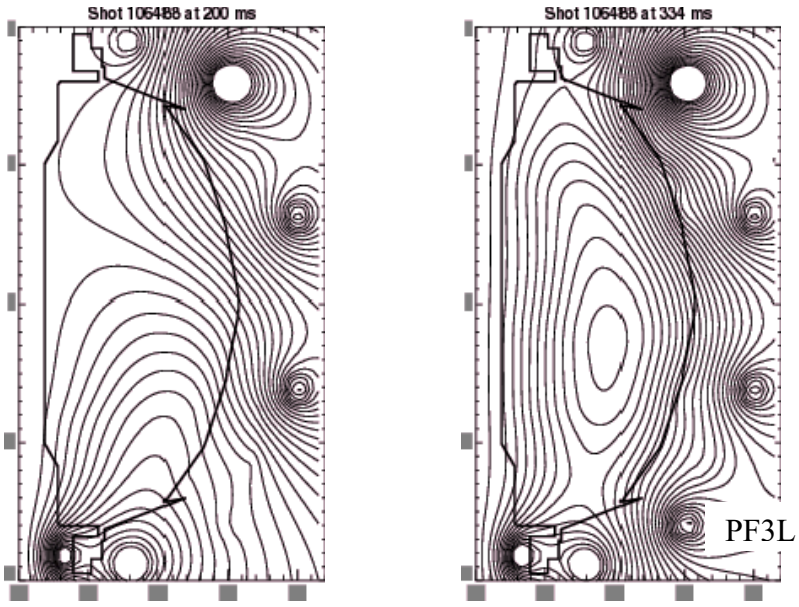


Figure 3: Flux contours calculated by MFIT at two times in the high current CHI discharge. The two lowermost coils are used to control the CHI injector flux. The third lower coil, seen on the right flux plot, is the PF3L coil that is used to make the transition from the "wide" to the "narrow" footprint. At 200ms, the current in this coil is nearly zero, which causes the flux footprints on the inner and outer electrodes to be spread far apart. At 334ms, the current in the PF3L coil is about -1.5kA, which causes the flux contours to approach those of a lower single null divertor discharge. A CHI produced discharge must reach this condition in order to apply other means of non-inductive current drive.