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# Solenoid free plasma production in NSTX by coaxial helicity injection

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## Abstract

Coaxial Helicity Injection (CHI) is a promising candidate for initial plasma generation and for edge current drive during the sustained operating phase. Experiments on NSTX thus far have succeeded in attaining 390 kA of CHI generated toroidal current in what is referred to as *steady-state* CHI, during which the CHI driven discharge could be sustained essentially indefinitely.

## 1. Introduction

To minimize the aspect ratio, elimination of the central solenoid is a consideration for future ST designs. In addition, advanced tokamak reactor designs, ARIES AT and RS, realize considerable cost savings by eliminating the central solenoid [1], which points to the importance of developing methods which can initiate solenoid-free closed flux current for plasma start-up. While there has been some work on current initiation by RF current drive in large tokamaks [2], these are yet to be adequately demonstrated on an ST. Furthermore these methods, which rely on the presence of a high quality field null in combination with the need for plasma equilibrium under rapidly evolving plasma equilibrium conditions, can greatly benefit from the presence of an initial closed flux equilibrium, which CHI start-up could provide [3]. Experiments on NSTX thus far have succeeded in attaining 390 kA of CHI generated toroidal current in what is referred to as *steady-state* CHI, during which the CHI driven discharge could be sustained essentially indefinitely. A new method recently developed on HIT-II, referred to as *transient* CHI, has unambiguously demonstrated the presence of a robust closed flux equilibrium and central transformer volt-seconds savings when coupled to induction, showing that the CHI produced plasmas are not only compatible with conventionally produced inductive plasmas but that they also improve the performance of these inductive plasmas [3]. In this method the plasma is rapidly grown through the use of an appropriately sized capacitor bank. The initial static magnetic flux is chosen such that this rapidly expanding plasma has a tendency to detach from the lower divertor electrodes.

Rapidly reducing the injector current during this phase eases the detachment process, which results in the production of a robust closed field line equilibrium. This method is scheduled to be tested on NSTX during the 2004 run campaign.

## NSTX experimental results

CHI is implemented on NSTX by driving current along field lines that connect the inner and outer lower divertor plates. In the *steady-state* CHI approach, which is described in this paper, 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 is used to drive the edge current. 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 sustainment current during the long pulse non-inductive phase.

Using the steady-state approach, experiments on NSTX thus far have succeeded in attaining 390 kA of CHI generated toroidal current [4]. Equilibrium reconstruction of this discharge shown in Figure 1 is reported in this paper. Since there can be substantial open field line current in a CHI produced discharge, any equilibrium reconstruction requires inclusion of open field line current. The Equilibrium and Stability code (ESC) developed by L. Zakharov of PPPL has been modified to include current capability on open filed lines and in the private flux region [5]. The current density as a function of radius is fitted to a polynomial basis function. A fifth order polynomial is used. The present version of the code uses a singular value decomposition technique to obtain a match between the measured and computed flux loop data, external poloidal Mirnov coil data and the poloidal field coil current data. Additionally, individual weights can be assigned to increase the priority given to the flux loop data, the external poloidal Mirnov coil data or to the coil current data. Although the code has capability to use vessel current data, because of lack of adequate vessel current measurements on NSTX, a low normalized weight (of 0.001) is given to the vessel current data. Weights of 1.3 for the flux loop data, 1.1 for the Mirnov coil data and a weight of 1 for the poloidal coil current data are assigned to obtain the best possible fit between the reconstructed and original data. The best fit is obtained at t = 332 ms, which corresponds to the highest toroidal current yet obtained in a CHI discharge. Reconstructed flux contours along with the computed radial current density profile at the plasma mid-plane is shown in Figure 2. This time also corresponds to near the end of the discharge. In using ESC it is found that the reconstructions give better fits during the current increasing phase of the large toroidal current oscillations seen in Figure 1. These large-scale oscillations could be due to large scale reconnection activity brought about by relaxation activity to flatten the current density profile. During the current drop phase, the reconstructions yield large errors or the code fails to execute, probably because the rapid changes in CHI equilibrium cannot be adequately represented by a 2-D equilibrium.

Fits showing a tendency for some closed flux are produced at the higher toroidal currents, and generally there is no tendency for any closed flux for toroidal current less than 200 kA. The computed results are consistent with closed flux generation, but one cannot conclude that closed flux surface have been produced because only external data is used. Additional experimental measurement from the plasma interior are needed as a consistency check of the equilibrium reconstructions. Nevertheless, the ESC code reconstructions provide guidance for future experiments. First, the reconstructions show the core plasma to be well below the machine mid-plane. This implies an experimental need to increase the vertical elongation of the discharge so that the CHI plasma core can be diagnosed using mid-plane diagnostics. This has been problematic because of the frequent occurrence of absorber arcs, which terminates the plasma discharge. The new improved absorber region, now installed on NSTX, should reduce the tendency for absorber arcs and allow improved experimental capability for generating higher elongation, higher current discharges. The reconstructions also show that a poloidal field coil in the upper part of the vessel is being over driven. Reducing the current in this coil should provide more space for the CHI plasma to expand near the top of the vessel. This should further facilitate flux closure and increase the plasma elongation. Finally, the observation that the best fits yet produced correspond to the highest toroidal current, during which phase the injector flux has been reduced and the injector flux footprints have been made narrow, indicates that present CHI discharges may be on the verge of producing good flux closure and further reducing the injector flux and further narrowing the injector flux footprints is probably needed to see consistent flux closure. The new NSTX absorber (the region containing the upper divertor plates) should be more resistant to spurious arcs enabling such an experiment to now be possible in NSTX.

For $\lambda_{inj} = \lambda_{tok}$, where $\lambda_{inj} \sim \mu_o I_{inj} / \Psi_{inj}$ and $\lambda_{tok} \sim \mu_o I_{tok} / \Psi_{toroidal}$, the current multiplication is given as $I_{toroidal} \sim I_{inj} * (\Psi_{toroidal} / \Psi_{inj})$. In these experiments, the injector flux is reduced over time [4]. Since $\Psi_{toroidal}$, which is determined by the toroidal field is approximately constant, at constant injector current, the current multiplication is expected to increases at later times, which is observed in the experiment.

In summary, 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 implement the transient CHI approach [3] for the purpose of plasma start-up, while we continue to explore the long pulse steady-state approach to investigate its potential for sustained edge current drive and scrape-off-layer flow modifications and for inducing edge plasma rotation for the purpose of sustaining transport barriers.

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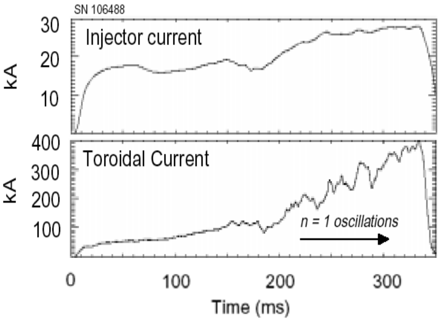

Figure 1: Long pulse, high current CHI discharge on NSTX. Shown are the current provided by the DC power supply and the CHI produced toroidal current.

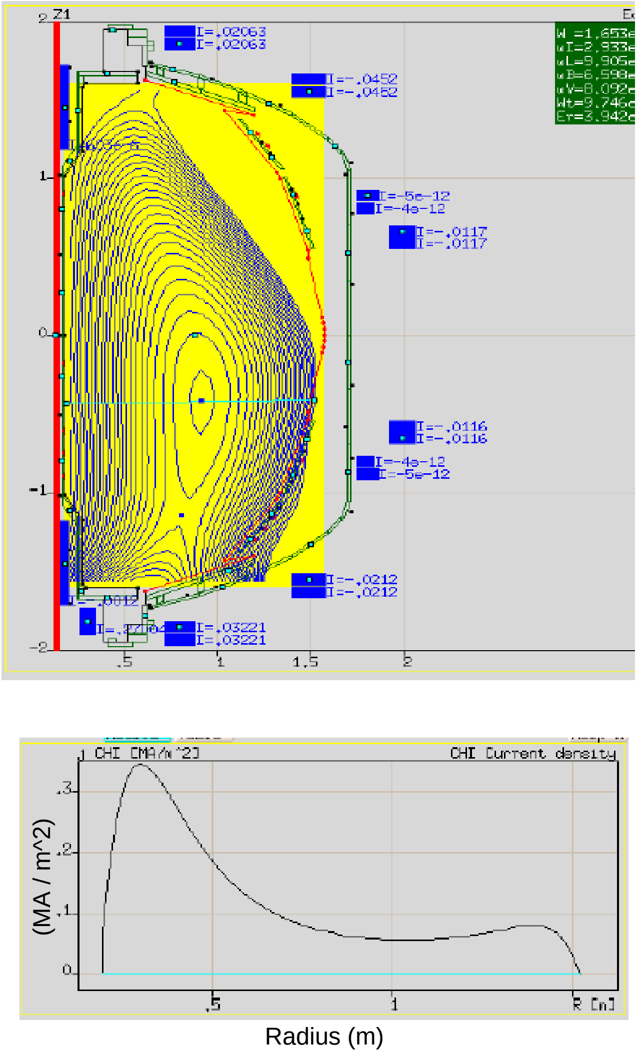

Figure 2: (left top and bottom) Equilibrium reconstruction of the discharge shown in Figure 1 during the high current phase at 332 ms using the ESC code. Shown are flux contours (top) and the radial current density profile (bottom). The shape of the current density profile is consistent with soft x-ray observations, which show emission primarily from the inboard side, which has a higher current density. This would contribute to more heating of the plasma on the inboard side.