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ORIGINAL PAPER

# Plasma Start-up in HIT-II and NSTX Using Transient Coaxial Helicity Injection

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**Abstract** The method of transient coaxial helicity injection (CHI) has previously been used in the HIT-II experiment at the University of Washington to produce 100 kA of closed flux current. The generation of the plasma current by CHI involves the process of magnetic reconnection, which has been experimentally controlled in the National Spherical Torus Experiment (NSTX) at the Princeton Plasma Physics Laboratory to allow this potentially unstable phenomenon to reorganize the magnetic field lines to form closed, nested magnetic surfaces carrying a plasma current up to 160 kA. This is a world record for non-inductive closed-flux current generation, and demonstrates the high current capability of this method.

**Keywords** CHI · ST · Non-inductive current drive

## Introduction

A method to start tokamak plasmas without using the central solenoid would provide access to lower aspect ratio configurations. As the aspect ratio is lowered the plasma performance and efficiency are projected to considerably improve [1]. A lower aspect ratio tokamak is capable of operating at higher values of the bootstrap current fraction and at much higher values of the plasma beta. Significant improvements to the plasma stability limits in conjunction with a high value of the bootstrap current fraction has now been verified in the large Spherical Torus, NSTX, which has attained toroidal plasma betas approaching 40% [2, 3]. New generation of tokamaks are designed to operate with long current pulse durations, approaching steady-state conditions. For a steady-state device, eliminating the inductive central solenoid simplifies the engineering design as shown by the ARIES reactor design studies, and allows flexibility in the reactor design to access lower aspect ratio configurations to improve overall reactor efficiency. Elimination of the central solenoid, however, requires a demonstration of plasma startup without the use of the central solenoid.

Coaxial helicity injection (CHI), a method originally developed for spheromak formation, is a promising candidate for both initial plasma startup and for providing edge current drive during the non-inductive sustained operation phase [4, 5]. On HIT-II [6] and on NSTX [7], CHI is implemented by driving current along externally produced field lines that connect coaxial electrodes mounted on the electrically isolated inner and outer vacuum vessel components in the presence of externally generated toroidal and poloidal magnetic fields.

## The HIT-II and NSTX Experiments

Figures 1 and 2 are the layout of the HIT-II and NSTX experiments. HIT-II was designed to study and develop CHI. HIT-II has major/minor radius of 30/20 cm and is capable of operating at up to 0.5 Tesla of toroidal magnetic field at the geometric axis and at an elongation of 1.7. The outer stainless-steel vacuum vessel is coated with tungsten. It is electrically isolated from a graphite-covered stainless-steel central column, as shown in Fig. 1. The lower part of the machine consisting of tapered coaxial electrodes is

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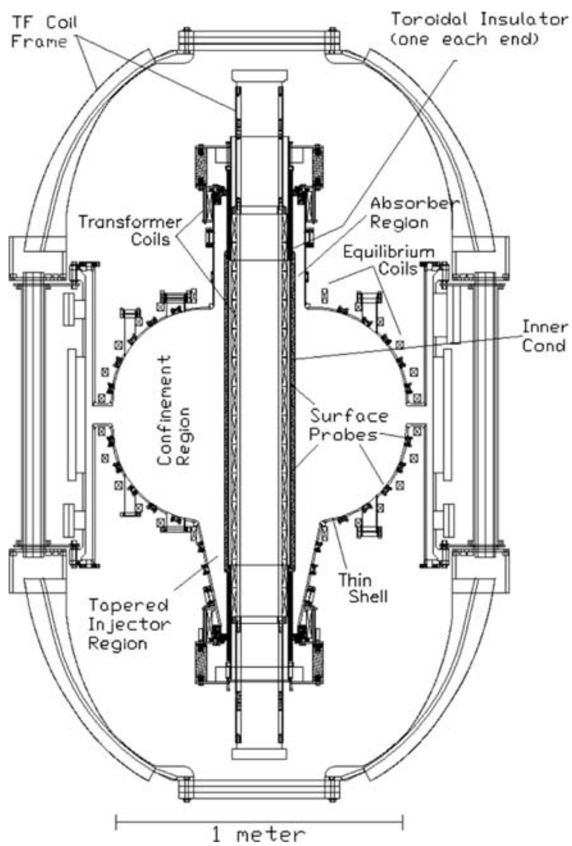


**Fig. 1** Layout of the HIT-II experiment showing the several close-fitting poloidal field coils and the absorber and injector regions

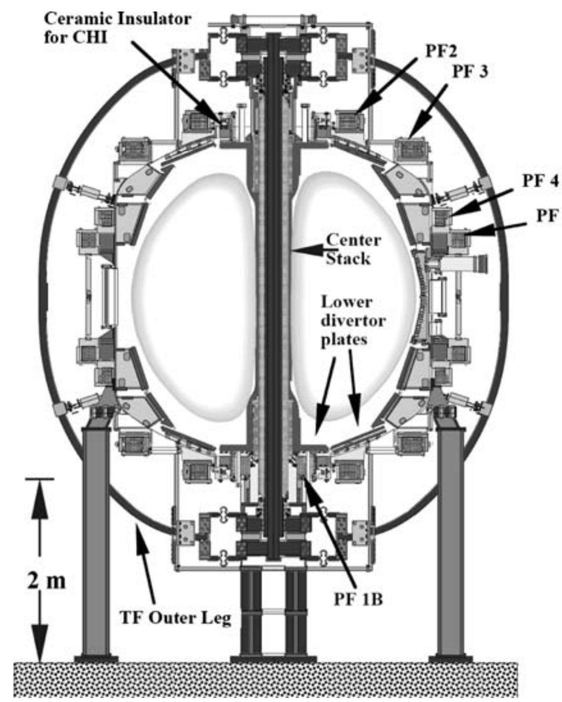


**Fig. 2** Layout of the NSTX device showing the few poloidal field coils that are much farther away from the plasma boundary than on HIT-II. NSTX uses the lower divertor plates as electrodes for CHI discharge initiation

referred to as the injector region, and functions as a magnetized coaxial plasma gun. The injector magnetic field is produced by several fast acting (sub ms time response) poloidal field coils closely surrounding the injector region. The untapered, opposite end is referred to as the absorber region, because the *ExB* plasma drift is away from the injector region and into the absorber region. Plasma injectors, located at two ports in the injector region are used to inject ionized gas in the injector gap annulus. CHI as well as inductive discharges on HIT-II benefit from the Titanium wall conditioning technique. Because the stainless-steel vacuum vessel is very thin (magnetic soak-through time of less than 1 ms) active feedback control, especially of CHI plasmas, is needed to sustain these plasmas. This is achieved using IGBT controlled feedback system that is used to actively control a system of 28 poloidal field coils, 14 of which are located inside the central column and 14 on the curved outer shells. Each of these coils is individually controlled by a power supply, which adjusts the coil current so that the poloidal flux measured by a nearby flux loop matches a preprogrammed demand.

Figure 2 shows a layout of the NSTX device. NSTX has a major/minor radius of 0.86/0.68 m and is capable of operation at a plasma elongation of up to 3. Unlike HIT-II, NSTX is configured much like a conventional tokamak. It has ten poloidal field coils (two of which are normally not used) located about 0.5 m away from the plasma boundary. In addition, the plasma benefits from passive stabilization from the copper passive plates located inside the vacuum vessel. The time response for the coil programmed flux to penetrate the structural components is typically about 6–10 ms, compared to less than 1 ms on HIT-II. A single power supply is used to drive the central solenoid. NSTX uses the lower divertor plates as the injector. During transient CHI operation gas is injected in a region below the divertor plates. During normal inductive operation approximately the same amount of gas needed for CHI operation (about 2 Torr l) is puffed directly into the vacuum vessel. As on HIT-II, the inner and outer vacuum vessels are electrically separated using two toroidal alumina ceramic insulators located in the injector and the absorber regions. The entire plasma facing boundary of NSTX is composed of graphite tiles. NSTX uses conventional Helium glow discharge cleaning as the wall conditioning technique. The NSTX vessel volume is 30 times larger than HIT-II.

## Experimental Results

In both machines, a CHI discharge is initiated by first producing poloidal field connecting the injector electrodes

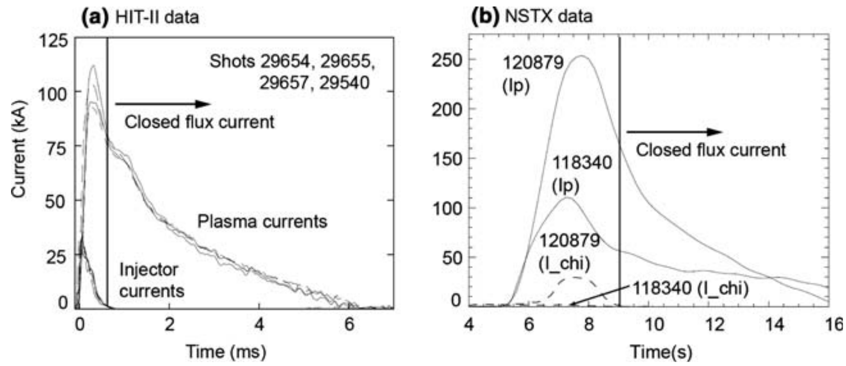


**Fig. 3** Transient CHI produced discharges in (**a**) HIT-II and (**b**) NSTX. The *vertical line* marks the time when the injector current has been reduced to zero. Beyond this time the CHI system is turned off. Plasma current persistence beyond this time is due to resistively decaying closed flux equilibrium

with poloidal field coils located outside the vessel structure. This poloidal field in combination with the toroidal field produces a helical field line structure in the injector region. Application of sufficient voltage to these electrodes in the presence of fuel gas causes the gas to breakdown. The resulting current flows on field lines connecting the electrodes. At sufficiently high injector currents, the resulting $\Delta B_{tor}^2$, $\mathbf{J}_{pol} \times \mathbf{B}_{tor}$, stress across the current layer exceeds the field line tension of the injector flux, causing the helical current structure to move into the main plasma chamber. The toroidal current is approximately the injected current times the ratio of the enclosed toroidal flux to the amount of injector flux that has extended into the vessel [4]. This process, referred to as *driven* CHI or *steady-state* CHI, can, in principle, be sustained indefinitely. Using this method, CHI discharges lasting up to 0.4 s have been produced on the NSTX device. It is important to note that the toroidal current produced by CHI initially flows on open field lines. Relaxation activity or other processes, such as forced axisymmetric reconnection, are needed to transfer some of this current onto closed field line regions. The creation of closed field line current in a driven CHI system, which is eventually needed for sustainment of non-inductive discharges, is a subject of ongoing research. However, the experiments described here and referred to as *transient* CHI, use pulses of CHI much shorter than the current relaxation timescale solely for the purpose of plasma current startup.

For transient CHI, the source current, referred to as the injector current, is provided by a small capacitor bank (0.5–4 mF at up to 2–4 kV on HIT-II and 20–45 mF at up to 1.8 kV on NSTX) that is connected across the outer and inner vessel components at the injector end of the machine. The capacitor power supply is switched by an ignitron and the circuit is over-damped by a series resistor.

Typical traces for a transient CHI produced discharge from HIT-II and NSTX are shown in Fig. 3. The vertical line marks the time when the injector current is reduced to zero. After this time the CHI circuit is no longer being actively driven. Thus the only plausible explanation for any persisting current past this time must be due to decaying closed flux equilibrium [6]. Fig. 3a shows that about 75 kA of closed flux current is generated in these discharges in HIT-II and that about 30 kA of injector current is needed. Figure 3b shows similar traces for two discharges from NSTX. Discharge 120879 has about 160 kA of closed flux current at the time of zero injector current. It is useful to note that the lower current discharge in NSTX has very small injector current of about 2 kA [7], and is almost irresolvable on this scale, showing the dramatic current multiplication possible in the much larger NSTX device. The larger magnitude of the injector current in discharge 120879 has been attributed to a condition known as an absorber arc. This is a condition when a second current path appears across the upper absorber insulator, causing most of the injected current to flow along the upper insulator surface. This current can be reduced by minimizing the poloidal fields in the region near the absorber gap or by reducing the size of the capacitor bank used to form the discharge so that the capacitor bank is mostly depleted of energy by the time the CHI discharge has filled the vessel. CHI discharges produced on HIT-II have also been shown to couple to induction and to outperform inductive-only plasmas [6]. Similar coupling studies on NSTX as well as optimization to reduce the extent of absorber arc current are the subject of future NSTX experiments.

The method of transient CHI has been show to work very well in HIT-II, consistently out performing inductive-only discharges. On NSTX, it has produced world record non-inductively generated start-up currents. It should be tried on large tokamaks.

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