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ORIGINAL PAPER

Solenoid-free Plasma Start-up in NSTX using Transient CHI

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Experiments in NSTX have now unambiguously demonstrated the coupling of toroidal plasmas produced by the technique of CHI to inductive sustainment and ramp-up of the toroidal plasma current. This is an important step because an alternate method for plasma startup is essential for developing a fusion reactor based on the spherical torus concept. Elimination of the central solenoid would also allow greater flexibility in the choice of the aspect ratio in tokamak designs now being considered. The transient CHI method for spherical torus startup was originally developed on the HIT-II experiment at the University of Washington.

Keywords CHI · ST · Non-inductive current drive

Introduction

The favorable properties of the Spherical Torus (ST) confinement concept arise as a result of its small aspect ratio [1]. Reactors based on the ST concept are projected to operate at very high values of the toroidal beta (>40%) and bootstrap current fraction (>90%) [2]. The capability of the ST to operate at high beta and high values of the bootstrap current fraction has been demonstrated on NSTX [3]. However, STs have limited space for a central solenoid, which restricts the inductive pulse duration, making solenoid-free plasma start-up and non-inductive sustainment necessary. Therefore elimination of the central solenoid is essential for the viability of the ST concept. Solenoid-free plasma startup is also relevant to steady-state tokamak operation, as this large inductive component that is located in a high radiation environment is needed only during the initial discharge initiation and current ramp-up phases. Removing the central solenoid provides greater flexibility in the selection of the aspect ratio and simplifies the reactor design.

Coaxial Helicity Injection (CHI) is a promising candidate both for plasma startup and for edge current drive during the sustained phase. The possibility of using CHI in a ST was first proposed in the late 1980s [4]. It was generally believed that the development of non-axisymmetric plasma perturbations are needed for plasma startup using the CHI process in STs. Indeed this technique was initially used in NSTX and in several other STs. However, in a significant new development during the past few years, it was shown that for the purpose of plasma startup, axisymmetric reconnection is adequate for producing a high quality startup equilibrium. The use of this new method referred to as *transient* CHI was first demonstrated on the HIT-II experiment at the University of Washington [5]. The method has now been successfully used on NSTX for a demonstration of solenoid-free plasma start-up and successful coupling to subsequent inductive drive. The method has now been successfully used in NSTX.

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Implementation of CHI in NSTX

NSTX has a major/minor radius of 0.86/0.68 m and is capable of operation at a plasma elongation of up to three. The poloidal field coils needed for equilibrium control are located about 0.5 m away from the plasma boundary. The NSTX plasma benefits from passive stabilization from the copper passive plates located inside the vacuum vessel. The entire plasma facing boundary of NSTX is composed of graphite tiles. NSTX uses conventional Helium glow discharge cleaning as the wall conditioning technique. Lithium coating of the lower divertor plates is being developed as an alternate wall conditioning method. The NSTX vessel volume is 30 times larger than HIT-II.

As shown in Fig. 1, CHI is implemented by driving current along externally produced field lines that connect the lower divertor plates in the presence of toroidal and poloidal magnetic fields. NSTX uses the lower divertor plates as the injector. The opposite end consisting of the upper divertor plates is referred to as the absorber region, because the $\mathbf{E} \times \mathbf{B}$ plasma drift is away from the injector region and into the absorber region. The initial injector poloidal field is produced using the lower divertor coils. This field connects the lower inner and outer divertor plates. About 2 Torr L of deuterium gas is injected in a region below the divertor plates and a 7 to 45 mF capacitor bank charged up to 1.75 kV is discharged across the lower divertor plates. This causes the gas to breakdown causing currents to flow along the poloidal field lines connecting the lower divertor plates. It is useful to note that earlier experiments in NSTX at a capacitor bank charging voltage of 1.5 kV or lower also benefitted from the use of electron cyclotron pre-ionization (EC-Pi) to initiate the discharge. The 18 GHz microwaves at 10 kW were also injected in the cavity below the lower divertor plates. However, as the capacitor bank charging voltage was increased to 1.7 kV, it was found that reliable breakdown could be established without the use of EC-Pi. As the injected current exceeds a threshold value, the $\mathbf{J} \times \mathbf{B}$ force exceeds the restraining force from the injector field lines, causing the injected field to pull into the vessel as shown in Fig. 1. Simultaneously the stored energy in the capacitor is depleted and the voltage and injector current decreases. If the injector flux footprints are sufficiently narrow then reconnection occurs near the injector region, causing the flux that has expanded into the vessel to reconnect near the injector region producing a closed flux equilibrium in the vessel, as shown in Fig. 1. During 2008, it is this closed flux current that was driven inductively to demonstrate coupling of the CHI produced current to conventional inductive operation.

Experimental Results

As shown in Fig. 1, approximately 1.5 kA of injector current produces nearly 100 kA of plasma current. The resulting current multiplication, defined as the ratio of the plasma current to injector current, is nearly 70. At 10 ms, with nearly zero injector current, about 60 kA of current remains on closed field lines. The highest amount of closed flux current produced in NSTX CHI discharges is 160 kA, which is a world record for non-inductively generated closed flux current is a ST or tokamak.

In Fig. 2, we show traces for the injector current, the plasma current, and the applied inductive loop voltage for a CHI started discharge that was coupled to induction. In this discharge 5 kA of injector current produces about 75 kA of toroidal current. During the decay phase of this current induction is applied from the central solenoid. The inductive loop voltage as well as the external poloidal field coil currents needed for equilibrium are pre-programmed. This causes the decaying plasma current to ramp-up and reach a peak value of 180 kA. Beyond 50 ms, the plasma current decreases because these yet un-optimized discharges are vertically unstable. Future optimization would correct for this, which would allow the current to reach several hundreds of kA. Shown also are images from a fast camera diagnostic that provides a fish-eye view of the discharge

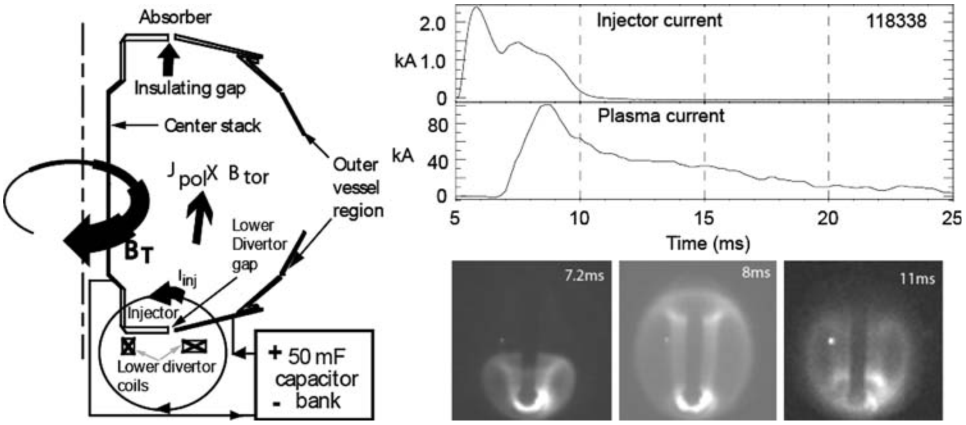

Fig. 1 Shown are: Left—line drawing to identify the main components needed for CHI operation, Right Top—CHI injector current and plasma current and Right Bottom—Fast camera fish-eye images for discharge 118338

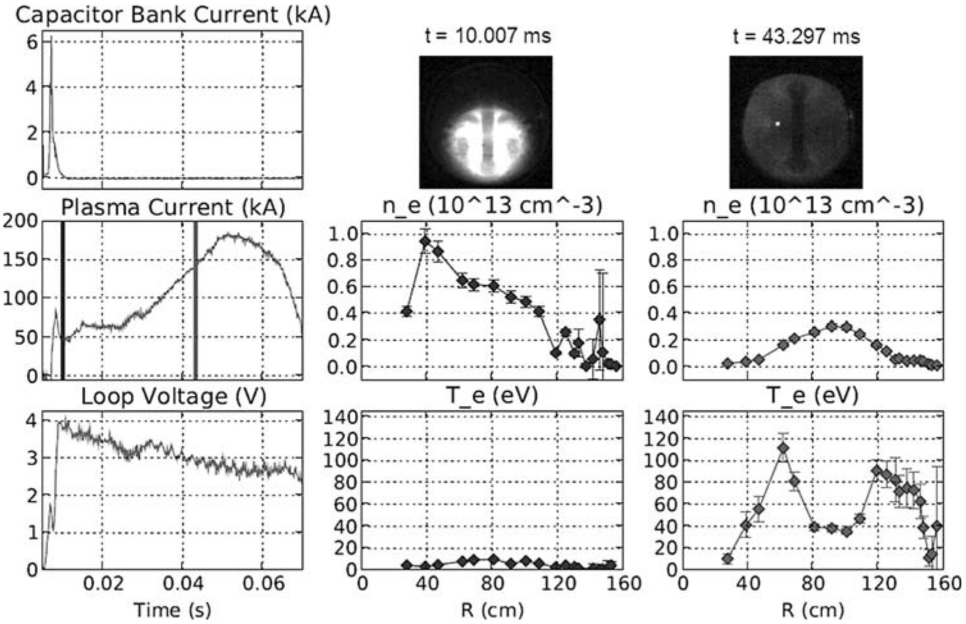

Fig. 2 Shown are from top to bottom: Left column—injector current, plasma current, loop voltage for discharge 128108, Middle column—camera image during the CHI phase, density and temperature profiles at 10 ms, Right column—camera image electron density and temperature profiles at 43 ms

evolution. Note that at early times corresponding to 10 ms, the plasma is evolving from the lower divertor region as a result of the injected current pulling the preprogrammed injector flux into the vessel. During the later image at 43 ms the plasma has nearly filled the vessel. The lack of emission is because the electron temperature has now exceeded levels where visible emission is essentially absent. This is shown in the figure, which shows the electron density to decrease in time and the electron temperature to increase in time.

The electron temperature profile at 43 ms is hollow, a feature that results from the fact that a CHI target was used, which uses edge current drive to produce the initial startup equilibrium. It is useful to note that the electron temperature at 10 ms is about 10 eV. Inductive heating increases this temperature to 100 eV at 43 ms. During this phase if an auxiliary heating system, such as electron cyclotron heating, were to be used, it would increase the plasma temperature. At an electron temperature >150 eV, the NSTX High Harmonic Fast Wave heating could be used to further increase the temperature to more than a keV. Applying induction to such plasmas would allow more efficient coupling of the inductive power as inductive power will not be used to heat the plasma.

Conclusions

While results such as this have been previously demonstrated on the smaller concept exploration HIT-II experiment, this is the first such demonstration on a large ST showing the exciting potential for the application of this method to future machines. In summary, the NSTX experiment generated a self contained ring of plasma carrying closed flux current which has been coupled to induction, for a demonstration of closed flux current generation and subsequent inductive coupling. Significant new achievements include a remarkable 60 times current multiplication factor of the injected current, which is an order of magnitude larger than achieved in previous experiments showing a favorable machine size scaling, and demonstration of the method in a vacuum vessel volume 30 times larger than HIT-II on a size scale and poloidal field configuration compatible to a compact ST reactor such as the Component Test Facility (CTF).

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