Physics of Flux Closure during Plasmoid-mediated Reconnection in Coaxial Helicity Injection

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Abstract: The fundamental reconnection mechanism that leads to the generation of closed flux surfaces in transient Coaxial Helicity Injection is examined using resistive MHD simulations. Transient Coaxial Helicity Injection (CHI) is a leading candidate for plasma start-up and current formation in NSTX-U. In NSTX, transient CHI has generated over 200 kA of toroidal current on closed flux surfaces without the use of the conventional central solenoid. To correctly model current generation and to better understand the physics of CHI start-up, comprehensive resistive MHD simulations have been conducted for the NSTX and NSTX-U geometries. It has been shown that magnetic reconnection has a fundamental role in the plasma start up and current formation in NSTX/NSTX-U. Here, we report two major findings from these CHI simulations: 1) formation of an elongated Sweet-Parker (S-P) current sheet and a transition to plasmoid instability has for the first time been demonstrated by simulations of CHI experiments and 2) a large-volume flux closure, and large fraction conversion of injected open flux to closed flux in the NSTX-U geometry have also now been demonstrated for the first time.

1. Introduction

In a low-aspect-ratio Spherical Torus (ST) and ST-based fusion reactor, ST-FNSF, due to the restricted space for a central solenoid, elimination of the central solenoid, and thus non-inductive current-drive techniques, is necessary. These methods could also simplify the tokamak design by eliminating a large component not needed during steady-state operations. Transient Coaxial Helicity Injection (CHI), a form of electrostatic helicity injection, first developed on the HIT-II experiment, [1] is the leading candidate for solenoid-free plasma start-up in NSTX-U. Transient CHI in NSTX has generated over 200kA of closed flux current without the use of the central solenoid. When induction from the solenoid was added, CHI initiated discharges in NSTX achieved 1 MA of plasma current using 65% of the solenoid flux of standard induction-only discharges [2]. On NSTX-U, transient CHI is the primary method for current generation without reliance on the solenoid. Simple models of CHI start-up indicate a current generation potential of over 400kA in NSTX-U, and about 2MA in a ST-FNSF [3,4]. In order to realize this potential, and to improve and better understand CHI start-up, comprehensive resistive MHD simulations have been conducted for the NSTX and NSTX-U geometries.

Unlike most traditional helicity injection techniques relying on dynamo current drive, in transient CHI, the observed good quality startup current is explained through axisymmetric magnetic reconnection alone [7,8]. This is advantageous for easier extrapolation of the concept to larger devices. Understanding the physics of magnetic reconnection during CHI is of great importance for the viability of this concept.

In CHI, an initial injected flux connecting the lower divertor plates is produced by driving currents in the lower divertor coils (shown in Figure 1 with numbers 1, 2 and 3) and a voltage applied to the electrically separated lower divertor plates to drive current along the

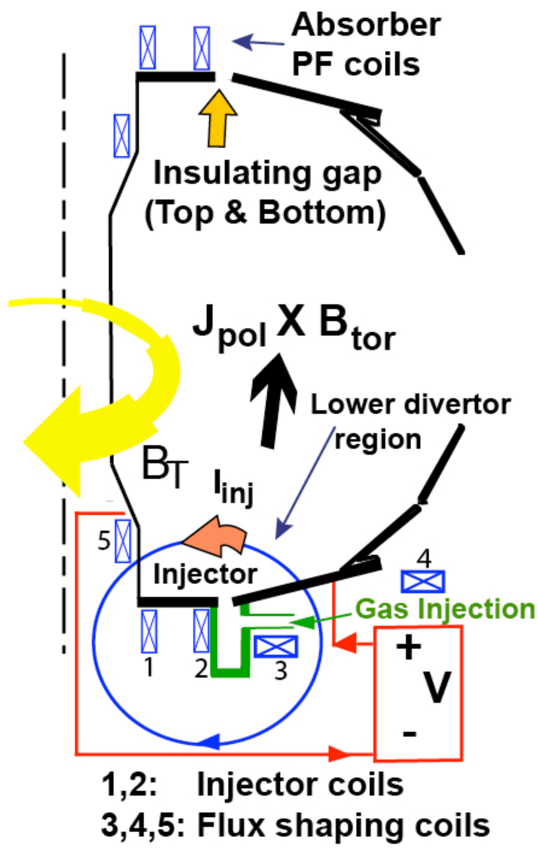

FIG. 1 Line drawing showing the main components in NSTX-U required for plasma start-up using CHI. The initial poloidal field, the injector-flux (shown by the blue ellipse), connecting the inner and outer divertor plates in the injector region is produced using the lower divertor coils (shown with numbers 1, 2). The primary injector coil (PF1CL) and the flux shaping coils (PF2L and PF1AL) used in the simulations are shown with numbers 2, 3 and 5, respectively.

open field lines, causing helicity and plasma to be injected into the device described in Reference [5]. Our resistive MHD axisymmetric NIMROD simulations are performed for a zero-pressure model with constant in time poloidal-field coil currents to generate the injector and shaping fluxes (fixed boundary-flux simulations) in both NSTX and NSTX-U. Simulations for NSTX and NSTX-U are presented in Section 2 and 3, respectively.

In NSTX-U, the CHI current start-up magnitude is projected to increase significantly as the result of several important upgrades for transient CHI. One of the most important of these upgrades is the improved positioning of the divertor coils which allows much better shaping of the injector flux. As shown in Figure 1, the injector coil is positioned much closer to the gap between the divertor plates. Our simulations, in support of planned experiments, are performed in the NSTX-U geometry by driving current in the lower divertor coils shown in Figure 1.

Other upgrades that are projected to improve CHI capability on NSTX-U are, higher toroidal field (1 T vs. 0.55 T on NSTX), twice the injector flux capability, planned higher applied CHI voltage, and planned implementation of 1 MW Electron Cyclotron Heating system.

2. Forced and spontaneous magnetic reconnection during CHI

In the simulations, the injection phase starts by applying a constant in time voltage at t=6ms in the presence of an initial poloidal injector flux and a vacuum toroidal magnetic field. The voltage is turned off at t=9ms (the decay phase), and we observe the reconnection process as the field lines are brought together by a radial force (forced reconnection). We find that there are two mechanisms for closed flux surface formation. In the first mechanism, referred to as forced reconnection, after the discharge fills the vessel, and the voltage is rapidly reduced to zero, a S-P type reconnection in the injector region is induced causing the formation of closed flux surfaces. The oppositely directed field lines in the injector region are forced to reconnect where a stable S-P current sheet forms (Fig.2 (a)). Sweet-Parker signatures including formation of an elongated current sheet, inflow pinch flows and outflows

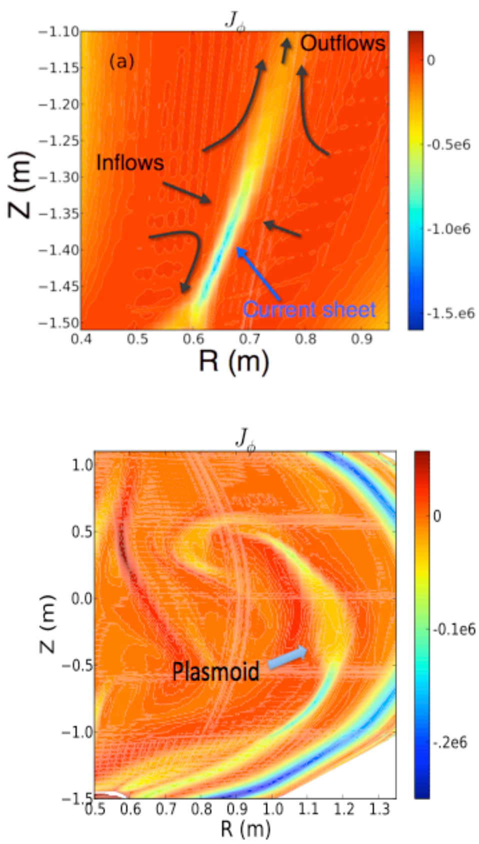

FIG. 2. Top: Elongated current sheet formation during forced S-P reconnection. Bottom: Current sheet breaks up due to spontaneous reconnection at high S.

along the elongated current sheet, and classical dissipative reconnection rates ($S^{-1/2}$ where S is the Lundquist number) were verified in the simulations. [7]

In the second mechanism, referred to as spontaneous reconnection, if helicity and plasma are injected into the device at high Lundquist number, the oppositely directed field lines in the injector region spontaneously reconnect when the elongated current sheet becomes MHD unstable due to the plasmoid instability (Fig.2 (b)). Consistent with theory, fundamental characteristics of the plasmoid instability are demonstrated through resistive MHD simulations. The transition to plasmoid instability is identified through: 1) the break up the elongated current sheet, 2) the increasing number of plasmoids with Lundquist number, and 3) the reconnection rate, as it becomes nearly independent of S. Our simulations show a transition to plasmoids instability occurs when the local Lundquist number exceeds a few thousands.

Motivated by the simulations, experimental camera images have been revisited and suggest the existence of reconnecting plasmoids in NSTX (see Fig.3). Our simulations suggest that plasmoid-mediated reconnection may be the leading mechanism for fast flux closure observed during the experiments.

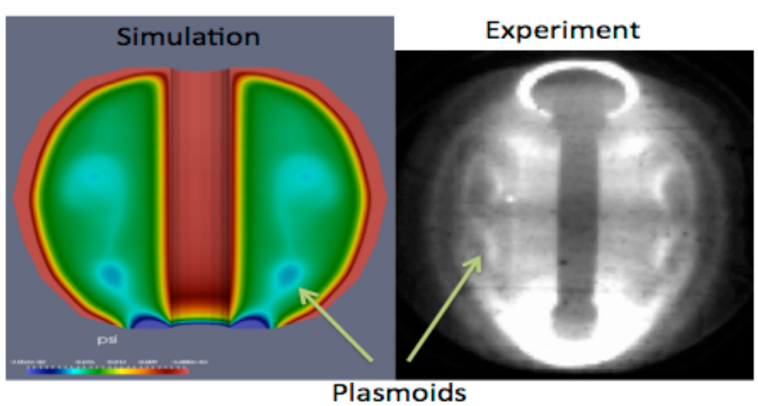

FIG. 3. Left: Plasmoid formation in simulation of NSTX plasma during CHI / Right: Fast-camera image of NSTX plasma shows two discrete plasmoid-like bubble structures.

3. Large volume flux closure in NSTX-U

Magnetic reconnection process explains the underlying physical mechanism for fast flux closure. However, to obtain maximum start-up plasma current, it is desirable for most of the injected open field lines (injector flux) to reconnect and form closed-flux surfaces. It is therefore important to explore the physics and conditions under which large volume of flux closure is obtained. We numerically examine the process of fast reconnection and the conversion of large fraction of injected open flux to closed flux surfaces using MHD simulations in the NSTX-U configuration. We find that the injector flux footprint has a critical role in obtaining a maximum flux closure. [6,8] With narrow injector flux footprint, which is achieved by driving parallel current in the primary injector flux coil and oppositely directed currents in the flux shaping coils (which are adjacent to the primary coil), a large volume of flux closure is formed (Fig.4) and almost all of the total current is in the closed flux region (with a large closed-flux current of about 240kA). With narrow flux footprint, fast flux closure occurs due to the enhanced reconnecting magnetic field (and local Lundquist number). With increased PF1AL flux shaping coil currents, the current sheet around the injection region becomes unstable even during the injection phase (while the injector voltage is on) and several plasmoids become unstable. These plasmoids shown in Fig. 4, are finally merged and after the voltage is turned off a large volume of flux closure is formed.

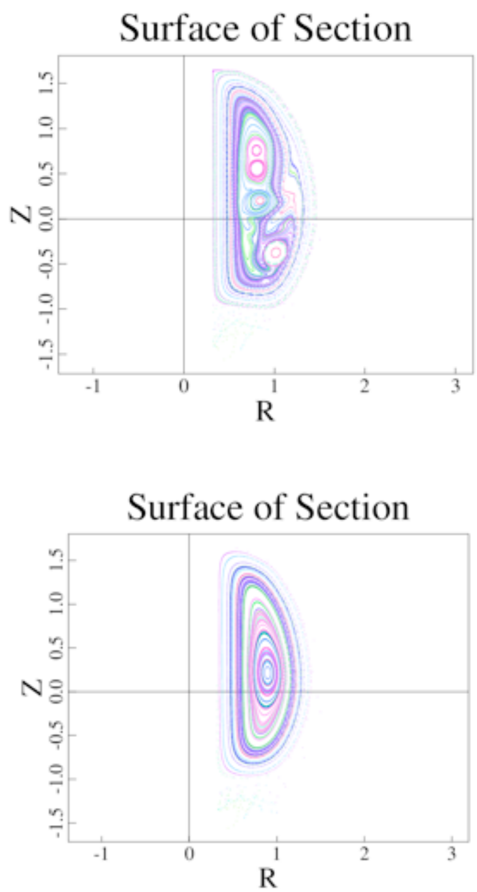

FIG. 4. The Poincare plots show large volume poloidal flux closure during NSTX-U simulations, about 70% of the initial injected flux (ψ_{inj} ~ 75 mWb) is closed. Top: at t=9.02ms right after the injection is turned off. Bottom: at t=9.5ms a large volume flux closure is formed.

4.0 Summary

These simulations suggest that as a result of the improved location of injector flux and shaping coils in NSTX-U, which allow a better shaping of the initial flux and attainment of narrower injector-flux footprints, major improvements and differences are elucidated in the NSTX-U simulations [6]: 1) the volume of flux closure is large and nearly all of the CHI-generated current is closed-flux current, 2) because of larger reconnecting magnetic field in the injection region, plasmoid instability could occur during the injection phase even at moderate temperatures. Simulations show that reconnection could occur at every stage of the helicity injection, but the final resulting state is a large volume of closed flux surfaces at equilibrium with a large CHI-generated closed-flux current.

5.0 Acknowledgments

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