Solenoid-free Plasma Start-up in HIT-II and NSTX using Transient CHI

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Elimination of the central solenoid is a consideration for the design of toroidal confinement devices, which then require alternative methods for initiating the plasma current. A new method of non-inductive startup, referred to as transient coaxial helicity injection (Transient CHI)[1, 2, 3], has been successfully developed on the Helicity Injected Torus, HIT–II, experiment [4], and recently implemented on the National Spherical Torus Experiment [5]. In this method, a plasma current is rapidly produced by discharging a capacitor bank between coaxial electrodes in the presence of toroidal and poloidal magnetic fields, shown schematically in Fig. 1. An initial very small gas puff is introduced near the injector, which is ionized by the applied voltage. The initial poloidal field configuration is chosen such that the plasma rapidly expands into the chamber. When the injector current is rapidly decreased, magnetic reconnection occurs near the injector electrodes, with the toroidal plasma current forming closed flux surfaces. By self-consistently increasing both the injector flux and the externally produced toroidal flux, the useful CHI-produced current on closed flux surfaces has been increased to 100 kA on HIT–II, and is retained during a subsequent inductive ramp. On HIT–II, CHI-started plasmas outperform discharges initiated by induction alone and consume less volt-seconds.[3]

Transient CHI is successfully used on NSTX for an unambiguous proof-of-principle demonstration of closed-flux current generation, of up to 160 kA, without the use of the central solenoid. Significant improvements over the HIT-II results are (a) demonstration of the process in a vessel volume thirty times larger than HIT-II on a size scale more comparable to a reactor, (b) a multiplication factor of 60 between the injected current and the achieved toroidal current, compared to six in previous experiments, and (c) significantly more detailed experimental measurements, including, for the first time, fast time scale visible imaging of the entire process, showing discharge formation, disconnection from the injector, and the reconnection of magnetic field lines to form closed flux. In some discharges the generated current persists for an unprecedented, and unanticipated 400 ms (until external equilibrium coils are shut off). These significant results, which were obtained on a machine designed with mainly conventional components and systems, indicate favourable scaling with machine size.

From helicity conservation, for a Taylor minimum energy state, $\lambda_{\rm inj} \geq \lambda_{\rm tok}$, where $\lambda_{\rm inj} =$

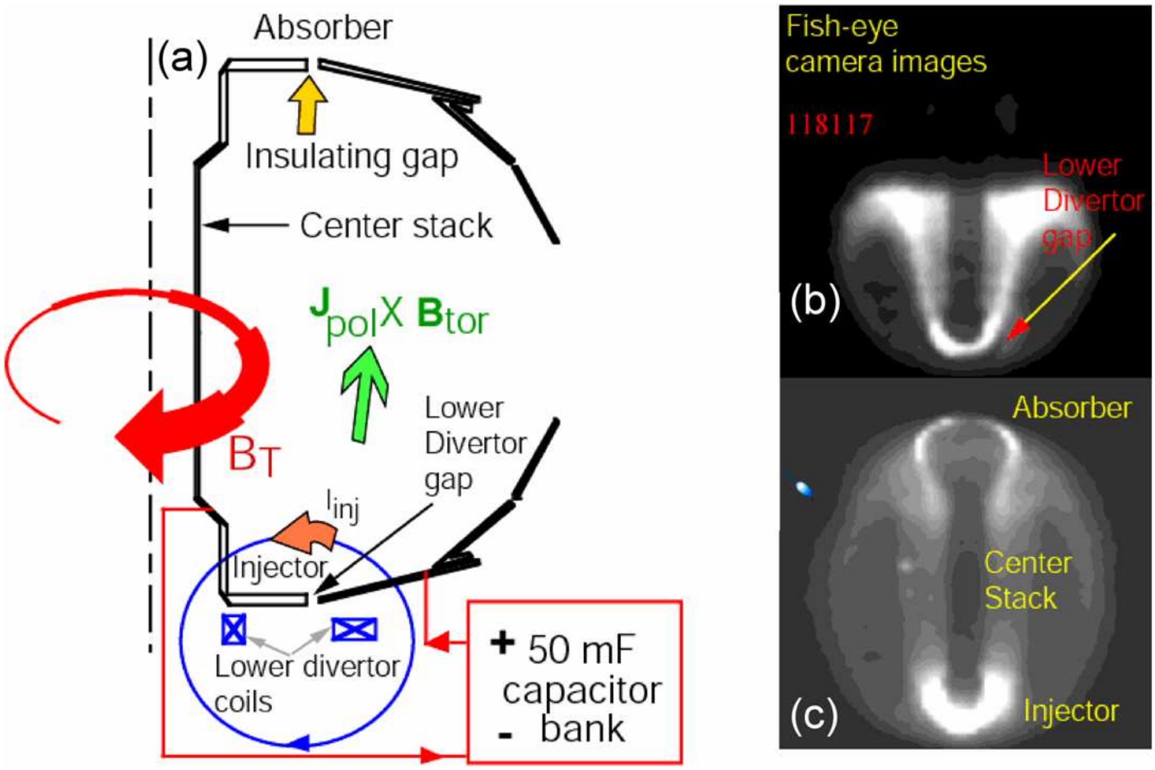

Figure 1: Schematic diagram of the application of CHI.

$\mu_0 I_{\text{inj}}/\psi_{\text{inj}}$, ψ_{inj} is the injector poloidal flux, and $\lambda_{\text{tok}} = \mu_0 I_p/\Phi_{\text{TOR}}$, where Φ_{TOR} is the vessel toroidal flux. This implies $I_p \leq I_{\text{inj}} \left(\Phi_{\text{TOR}}/\psi_{\text{inj}}\right)$. For the same B_T, NSTX has ten times the Φ_{TOR} of HIT–II, thus we expect for the same conditions, a greater ratio of toroidal to injector current in NSTX.

Details of HIT–II transient CHI results are reported elsewhere [1, 2, 3], while this paper focuses on recent NSTX results.

NSTX has added a capacitor bank for transient CHI, consisting of (up to) ten 5 mF/2 kV capacitors, switched by a single D-size ignitron. An additional crowbar ignitron is used to switch in a 20–50 mΩ resistor to aid the rapid reduction of injector current. For the results presented here, 9 capacitors, charged up to $\sim$ 1.75 kV are used. Multiple MOVs and an RC snubber are located at the NSTX vessel for transient voltage protection.

Waveforms for the NSTX plasma current I_p and injector current I_{inj} are shown in Fig. 2. A rather small I_{inj} (a few kA) rapidly produces a large toroidal plasma current (over 200 kA). (A parasitic, but benign, current flows at the flux absorbing insulator at the top of the NSTX vessel, increasing the total injector current to approximately 30 kA.) After the crowbar ignitron helps exhaust the transient CHI capacitor bank, a persistent toroidal current, up to 160 kA, is observed, lasting several milliseconds.

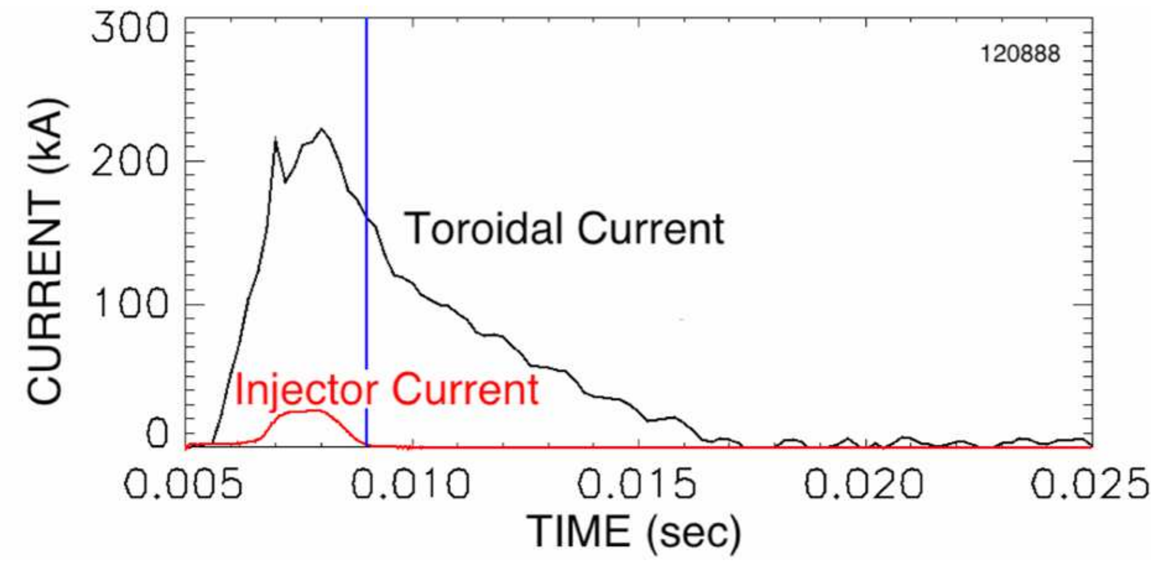

Figure 2: Time waveforms of NSTX toroidal plasma current and injector current. $I_{\rm inj}$ is essentially zero after $\sim$ 9 ms.

Fast video imaging (68000 frames per second) of the transient CHI process, Fig. 3, shows the initial pushing out of the injector flux, the filling of the vessel, and a closed object after the injector current is reduced to zero. The EFIT equilibrium reconstruction code produces equilibria consistent with the position and shape of the the video images.

Multi-point Thomson scattering (MPTS) data for lower capacitor bank charge voltages, and hence lower closed current ($\sim$80–100 kA) show 30-40 eV electron temperatures, with initially hollow densities, that later fill in. (The MPTS diagnostic was not available for the higher current ($\geq$ 150 kA) discharges.)

Very long-lasting current persistence is occasionally observed, with 20–30 kA of toroidal current lasting until the poloidal equilibrium field coils are de-energized at 400 ms into the discharge. Video images show these plasmas to emit diffuse light, with an occasional intersection of the plasma edge with the central column or outer vessel. (The higher closed-current discharges are of more interest for startup.)

In summary, initial experiments on NSTX continue the successful development experiments of transient CHI on HIT–II. High-quality, long-lasting, closed-current plasmas are formed with I_p up to 160 kA, which are, to our knowledge, the highest non-inductive startup plasmas yet produced. Fast video imaging shows the process of detachment and a closed-current object persisting for several milliseconds after the injector current has been reduced to zero. This result is extremely encouraging for non-solenoid startup scenarios. Future run campaigns on NSTX will optimize the current (expecting it to increase by using increased voltage), and also use this

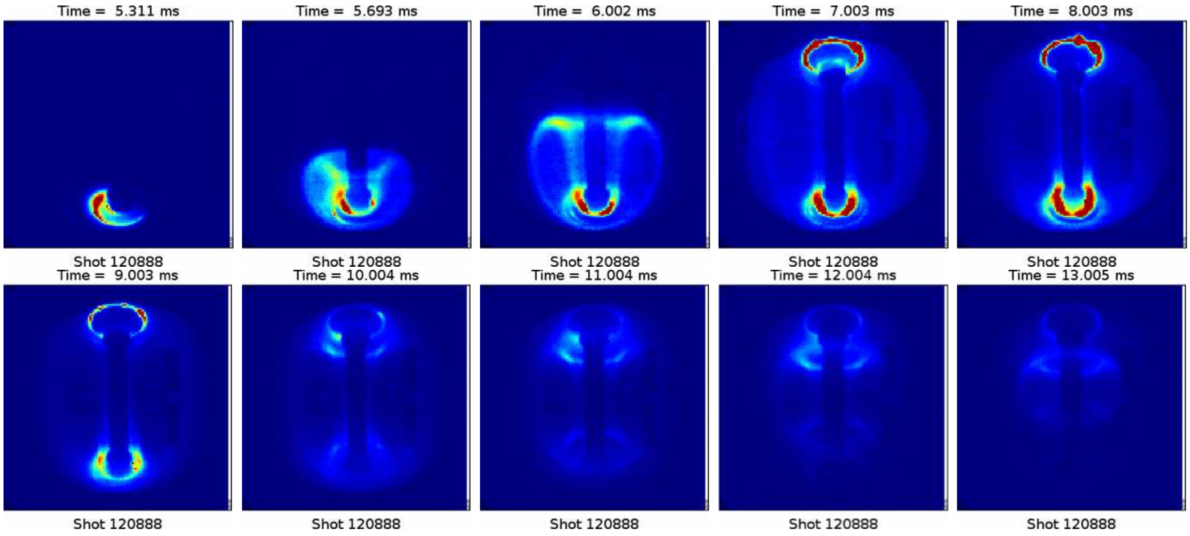

Figure 3: Fast false-color video images of a transient CHI discharge. (The waveforms, and time-base, for toroidal and injector currents are given in Fig. 2).

closed-current target for other current drive and heating techniques such as transformer action, neutral beam injection, and/or high harmonic fast waves.

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