

Coaxial Helicity Injection Non-inductive Startup on NSTX

B.A. Nelson¹, R. Raman¹, T.R. Jarboe¹,
D. Mueller², M.G. Bell², B. LeBlanc², A.L. Roquemore², H.W. Kugel²,
V. Soukhanovskii³

¹ *University of Washington, Seattle WA, USA*

² *Princeton Plasma Physics Laboratory, Princeton NJ, USA*

³ *Lawrence Livermore National Laboratory, Livermore CA, USA*

Abstract

Plasmas initiated by non-inductive transient coaxial helicity injection (CHI) have been successfully coupled to Ohmic ramp-up to achieve high-quality discharges in NSTX, reaching 800 kA and exhibiting H-mode. Conditioning of the divertor regions is found to improve both transient-CHI startup currents and coupling. Flux savings of transient-CHI startup plasmas over Ohmic ramp-up-only discharges has been demonstrated.

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. The transient coaxial helicity injection (Transient CHI) [1, 2, 3] method of non-inductive startup, successfully developed on the Helicity Injected Torus, HIT-II, experiment [4], is implemented on the National Spherical Torus Experiment (NSTX) [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, introduced near the injector, 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 decreases as the capacitor's charge is depleted, magnetic reconnection occurs near the injector electrodes, with the toroidal plasma current forming closed flux surfaces. With careful conditioning of the divertor surfaces and minimizing the amount of injected gas, high-quality CHI-produced closed flux currents can be coupled to subsequent Ohmic current drive, and demonstrate flux savings. [6] (Details of HIT-II transient CHI results have been reported previously [1, 6, 7], while this paper reports recent NSTX results.)

From helicity conservation, for a Taylor minimum energy state, $\lambda_{inj} \geq \lambda_{tok}$, where $\lambda_{inj} = \mu_0 I_{inj} / \psi_{inj}$, ψ_{inj} is the injector poloidal flux, and $\lambda_{tok} = \mu_0 I_p / \Phi_{TOR}$, where Φ_{TOR} is the vessel toroidal flux. This implies $I_p \leq I_{inj} (\Phi_{TOR} / \psi_{inj})$. For the same B_T , NSTX has ten times the Φ_{TOR} of HIT-II, thus, as expected, for the same conditions, a greater ratio of toroidal to injector current in NSTX.

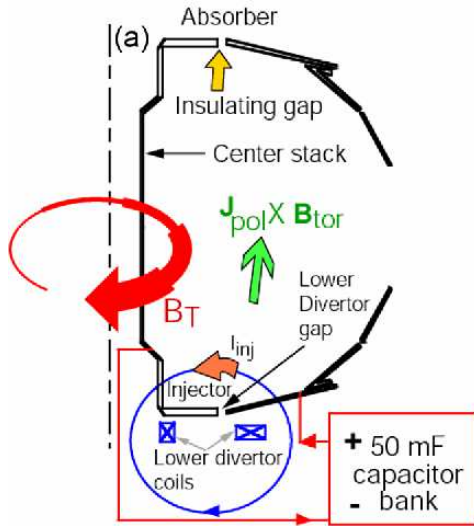


Figure 1: Schematic diagram of the application of CHI in NSTX.

Transient CHI is performed on NSTX *via* a capacitor bank consisting of (up to) ten 5 mF/2 kV capacitors, switched by up to three D-size ignitrons. An additional crowbar ignitron is used to switch in a 20–50 m Ω resistor to aid the rapid reduction of injector current. For the results presented here, capacitors, charged up to ~ 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). (On this particular discharge, a parasitic 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.

Fast video imaging (68000 frames per second) of the transient CHI process, Fig. 3, shows the injector flux being pushed out, filling the vessel, and a closed-flux 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 show 30 – 40 eV electron temperatures, with initially hollow densities, that later fill in. These values are consistent with Ohmic-only startup plasmas at similar times and currents.

Closed-flux currents have been successfully coupled to subsequent Ohmic drive, producing high-quality discharges on the order of 800 kA, including H-mode plasmas (when neutral beams are injected — NBI). As was found on HIT-II, to successfully couple transient CHI discharges to Ohmic ramp-up, it is crucially important to properly condition both

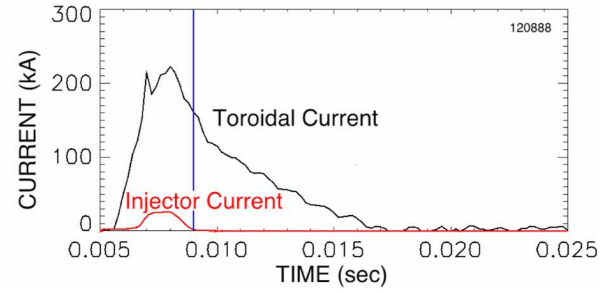


Figure 2: Time waveforms of NSTX toroidal plasma current and injector current. I_{inj} is essentially zero after ~ 9 ms.

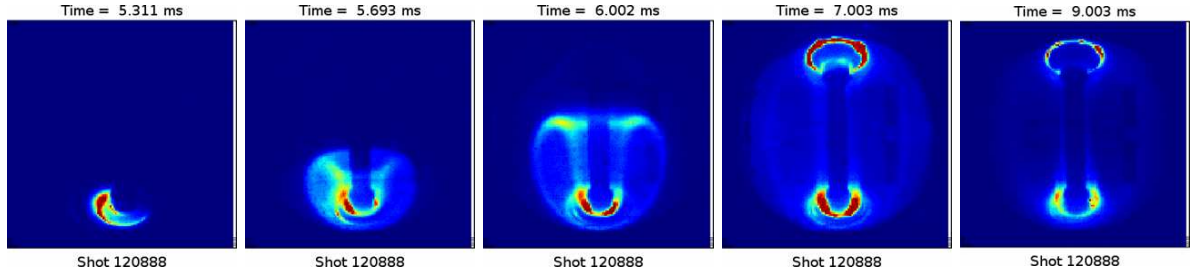


Figure 3: Fast false-color video images of a transient CHI discharge. (The waveforms, and time-base, for toroidal and injector currents are given in Fig. 2).

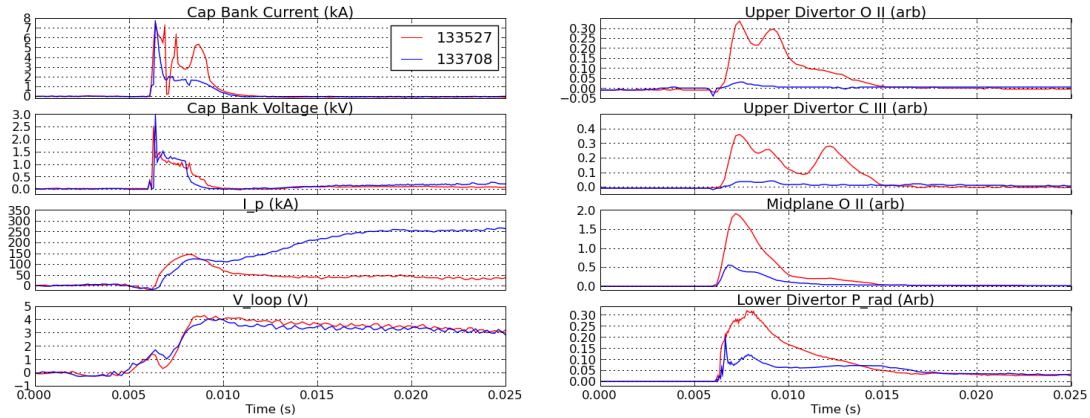


Figure 4: Comparison of radiation levels before (red) and after (blue) conditioning the divertors.

the upper and lower divertor surfaces to minimize any impurity radiation. Conditioning was accomplished by 1) running long pulse CHI discharges (~ 0.4 s at $\sim 5\text{--}6$ kA with a DC supply) with flux boundary conditions such that I_{CHI} was at or below “bubble-burst”, with D_2 DC glow discharge cleaning between shots, and 2) lithium evaporation using the NSTX LITER system during the transient-CHI discharges.[8] Similar CHI discharges (using 2 capacitors) are shown in Fig. 4, where the red traces are before conditioning and the blue traces are after conditioning. Also, after this more thorough conditioning, transient CHI handoff to Ohmic was, for the first time, successful with 2 and 3 capacitors, rather than just one, and the highest yet achieved handoff currents in transient CHI plasmas, ~ 140 kA.

Ohmic ramp-up of transient-CHI startup plasmas have also shown flux savings, as demonstrated in Fig. 5. Note for identical programming of OH coil current (and V_{loop}), the discharge with transient-CHI startup (blue) had nearly the same values of internal inductance and plasma major radius from EFIT. (These discharges underwent internal reconnection events after about 0.1 s, and are not necessarily comparable after these times.)

In summary, 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 pro-

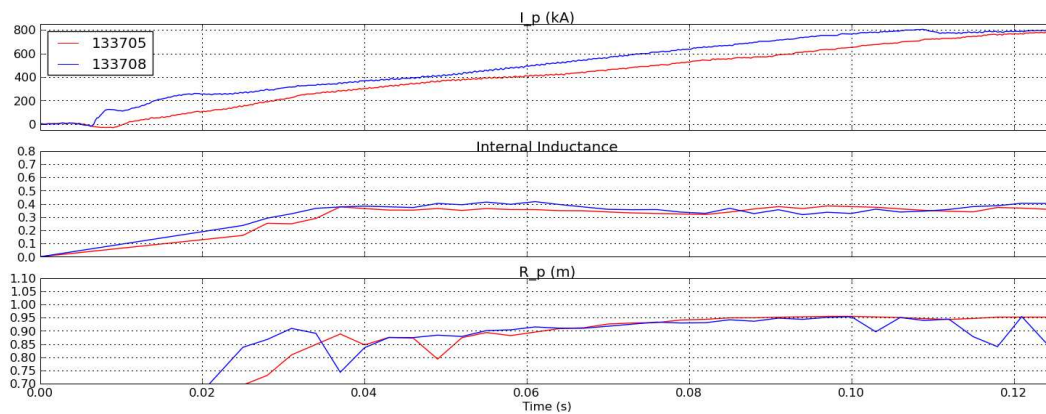


Figure 5: Demonstration of flux savings with transient-CHI startup (blue) over OH-only startup (red). (No NBI for these discharges.)

duced. Transient CHI plasma currents up to 140 kA have been coupled with subsequent Ohmic ramp-up to $I_p \sim 800$ kA, demonstrating flux savings, and with NBI, have produced H-mode plasmas. These results are extremely encouraging for non-solenoid startup scenarios. Future run campaigns on NSTX will be to increase and optimize the handoff current, continue divertor conditioning, and to minimize/eliminate absorber current using field coils near the absorber insulator.

References

- [1] R. Raman, T.R. Jarboe, B.A. Nelson, V.A. Izzo, R.G. O'Neill, A.J. Redd and R.J. Smith, *Physical Review Letters*, **90**, 075005/1, (2003)
- [2] R. Raman, T.R. Jarboe, D. Mueller, B.A. Nelson, M.G. Bell, M. Ono, *et al.*, *Physics of Plasmas*, (14)5:056106, 2007
- [3] R. Raman, T.R. Jarboe, D. Mueller, B.A. Nelson, M.G. Bell, R. Bell, *et al.*, *Nuclear Fusion* 49, p. 065006, June 2009
- [4] A. J. Redd, T. R. Jarboe, W. T. Hamp, B. A. Nelson, R. G. O'Neill, and R. J. Smith, *Physics of Plasmas*, Vol. 15, p 022506, 2008
- [5] M. Ono *et al.*, *Plasma Physics and Controlled Fusion*, **45**, A335, (2003)
- [6] R. Raman, T.R. Jarboe, R.G. O'Neill, W.T. Hamp, B.A. Nelson, V.A. Izzo, A.J. Redd, P.E. Sieck and R.J. Smith, *Nuclear Fusion*, **45**, L15-19, (2005)
- [7] R. Raman, T.R. Jarboe, B.A. Nelson, W.T. Hamp, V.A. Izzo, R.G. O'Neill, A.J. Redd, P.E. Sieck and R.J. Smith, *Physics of Plasmas*, **11**, 2565, (2004)
- [8] H.W. Kugel, M.G. Bell, J.-W. Ahn, J.P. Allain, R. Bell, J. Boedo, *et al.*, *Physics of Plasmas*, v 15, n 5, p 056118-1-13, May 2008