Coaxial Helicity Injection for the generation of non-inductive current in NSTX*

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The Spherical Torus is a magnetic confinement concept that has the advantages of high beta, increased stability and a projected high fraction of bootstrap current drive. These favorable properties of the ST arise from its very small aspect ratio (A ≤ 1.5). To minimize the aspect ratio, elimination of the central solenoid is a consideration for future ST designs. This requires the demonstration of plasma creation and sustainment by non-inductive current drive schemes. Coaxial Helicity Injection (CHI) is a promising candidate for initial plasma generation and for edge current drive during the sustained phase. The first experiments to explore this concept were successfully conducted on the HIT and HIT-II experiments at the University of Washington [1]. Related current drive experiments were also conducted on CDX-U at PPPL [2].

CHI is implemented on NSTX by driving current along field lines that connect the inner and outer lower divertor plates. A 25kA, 1kV DC power supply is connected across the inner and outer vessel components, as shown in Figure 1, to drive the injector current. On NSTX the central

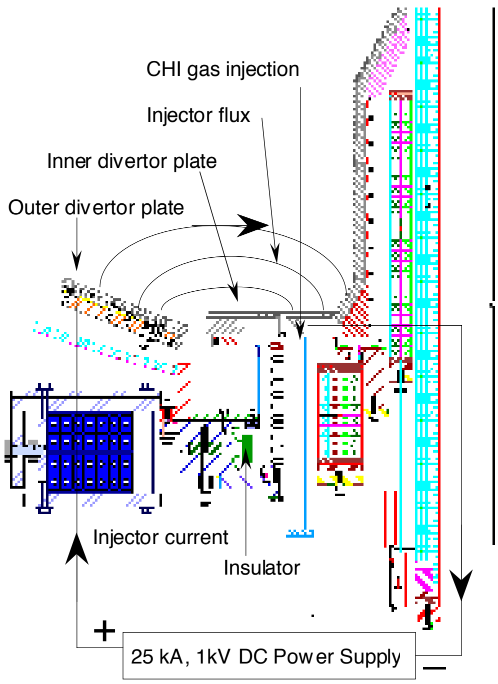

Figure 1: CHI components on the lower divertor region of NSTX.

column and the inner divertor plates (the inner vessel components) are insulated from the outer wall and the outer divertor plates, as on HIT-II.

An important goal for the NSTX program is to conduct the proof-of-principle experiments to validate this concept on a device that has a volume about 30 times that of HIT. Figure 2, shows a CHI discharge evolution as recorded by a fast camera. At t=16ms, the discharge originates in the lower divertor plate region. As the injector current increases, the fluxes connecting the lower divertor plates are extended into the confinement chamber (t = 18ms). At even higher injector currents, the discharge nearly fills the entire chamber (at t = 20ms).

Figure 3, shows the injector voltage, divertor coil current, injector current and CHI produced toroidal current, for a high current discharge. The divertor coil current is a measure of the poloidal flux that connects the lower divertor plates (see Figure 1). The applied voltage determines the amount of injector current that can be driven for this combination of injector flux and divertor gas pressure. This discharge has two phases. For times less than 50ms (phase 1), the applied voltage and the divertor coil current are constant. This results in an injector current of 20kA and a toroidal current of 50kA (a current multiplication factor of ~2). During phase 2 (t > 50ms), the divertor coil current is ramped down, which results in reduced injector flux. At lower injector flux, the injector impedance increases. To compensate, the injector voltage is increased as shown in Figure 3. The programmed voltage ramp maintains a constant injector current. Since the injector flux is decreasing with time, while the toroidal flux is constant, one expects the current multiplication factor to increase. Indeed, the toroidal current increased during the course of the discharge, resulting in a maximum of about 130kA at t = 100ms, a current multiplication factor of 6.5. The discharge for the entire duration was maintained in equilibrium using pre-programmed coil currents only.

Energy conservation and helicity balance require that the ratio of the current to the flux of the injector ($\lambda_{inj} = \mu_o I_{inj}/\Psi_{inj}$) must be larger than that of the ST ($\lambda_{ST} = \mu_o I_{toroidal}/\Psi_{toroidal}$) [3]. During steady state current drive, the efficiency for current drive is given as, $\varepsilon = \lambda_{ST}/\lambda_{inj}$ [3,4]. Thus the maximum current multiplication is predicted to be the ratio of the ST flux over the injector flux. For the shot shown in Figure 3, Figure 4 shows the ratio of the toroidal flux to injector poloidal flux multiplied by the injector current and compared to the measured toroidal current. This analysis shows that within uncertainties the amplification factor is nearly as large as possible (at t = 110ms). The measured current approaches 80% of the theoretical maximum current showing that CHI is very effective on large devices. The ratio is low during the early part of the discharge as only a small portion of the maximum possible toroidal flux (1.5Wb) links the injector flux. Even at t = 110ms, Magnetic Fitting Code (MFIT) and Tokamak Simulation Code (TSC) simulations [5], show that the injector flux does not fully fill the vessel which results in an overestimate of the ST flux that links the injector flux.

Figure 3 also shows an increase in voltage fluctuations during phase 2 of the discharge. The fluctuations have a coherent mode at ~9kHz. Analysis of the Mirnov coil signals shows a similar global mode during phase 2. A toroidal Mirnov array on the center column shows the magnetic signature of the discharge to be toroidally symmetric with a coherent n=0 mode. There is no toroidal Mirnov array on the NSTX outer vessel to discern the toroidal mode number near the outer shell. On the HIT experiments, a n=1 coherent mode activity, located on the outer shell probes only, is seen during high current discharges [1,6]; n = 0 activity is also seen by the outer Mirnov's in some discharges. On NSTX, coherent fluctuations were also seen by a fast photodetector that sampled a chord passing through the center of the plasma. This mode activity seen by both magnetic and optical diagnostics is deemed necessary for the formation of closed flux surfaces. However, there is insufficient data at present to conclusively prove the generation of closed flux surfaces in these early discharges.

To examine the effect of injector impedance at lower pressure, a scan was conducted in which the injector current was measured as the vessel pressure was reduced from 16 to 4mTorr. It was found that there is little change in injector current as the pressure is reduced. Experiments were also successful in generating discharges at a pressure of 1mTorr. Since pressures of about 4mTorr are compatible with high recycling divertor operation, these results indicate that on NSTX, from a density standpoint,

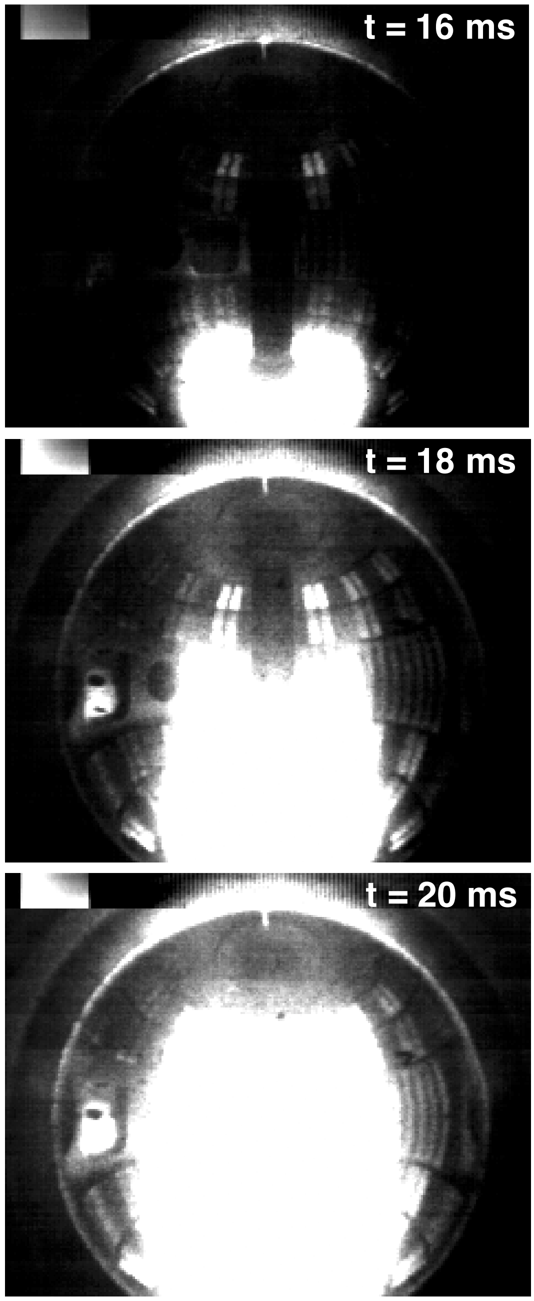

Figure 2:The fast camera fish-eye-view images show that the CHI produced plasma starts at the lower divertor region at 16ms, elongates to fill half the vessel at 18ms and then nearly fills the vessel at t = 20ms (SN 101044).

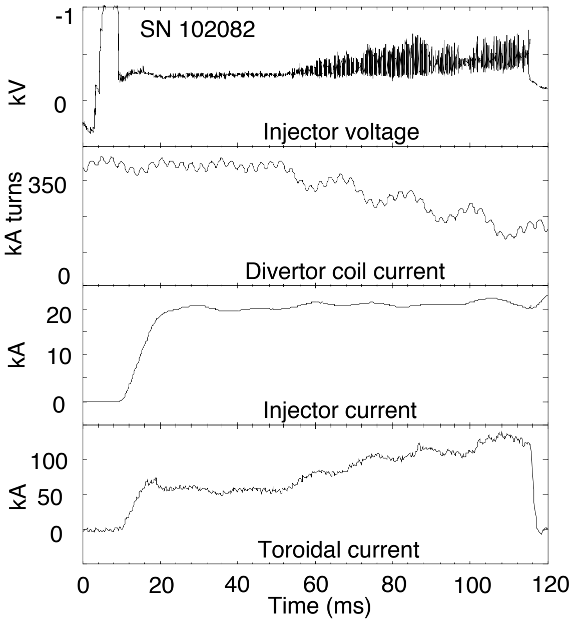

Figure 3: High current CHI discharge on NSTX using pre-programmed coil currents for equilibrium control.

it should be possible to couple CHI discharges to Ohmic discharges. Compared to similar measurements on HIT-II, these results indicate a more favorable density scaling of the injector impedance that very likely results from the longer field line length on NSTX.

In summary, initial CHI experiments on NSTX have successfully generated 130kA of toroidal current using about 20kA of injector current. Different flux configurations for the initiation of the CHI discharge have been tried. The highest current multiplication factor thus far obtained has been 10. Stable discharges lasting for 0.13 seconds have been produced using pre-programmed coil currents and at vessel neutral densities compatible with high recycling divertor operation. These results demonstrate that

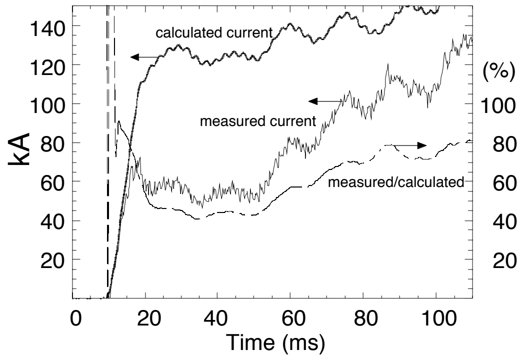

Figure 4: Measured and calculated ($I_{toroidal} = (\Psi_{toroidal}/\Psi_{inj})^* I_{inj}$) toroidal currents shows that the measured current approaches 80% of the maximum possible current.

there are no fundamental obstacles to applying CHI in a large plasma device.

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* Work supported by U.S. D o E contract numbers. DE-AC02-76CH03073, DE-AC05-00R22725, DE-AC03-99ER54463, DE-FG02-99ER54524, DE-FG03-99ER54519, W-7405-ENG-36