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Transient CHI for Solenoid-free Plasma Startup in NSTX*

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Elimination of the central solenoid is a consideration for future toroidal confinement devices which will then require alternative methods for initiating the plasma current. A method of non-inductive startup, referred to as coaxial helicity injection (CHI) is being investigated on the National Spherical Torus Experiment (NSTX). As shown in Figure 1, CHI is implemented on NSTX [1] by driving current along field lines that connect the inner and outer lower divertor plates, which are electrically insulated from each other by ceramic rings at the bottom and top. The plasma current is produced by discharging a capacitor bank between these coaxial electrodes in the presence of toroidal and poloidal magnetic fields. The initial poloidal field configuration is chosen such that the plasma rapidly expands into the chamber. When the injected current is rapidly decreased, magnetic reconnection occurs near the injection electrodes, with the toroidal plasma current forming closed flux surfaces. The method has been successfully developed on the HIT-II experiment to produce 100 kA of closed-flux toroidal current [2].

1. Requirements for Transient CHI

For the transient CHI process the capacitor bank must satisfy certain requirements. First there must be sufficient energy in the capacitor bank to produce the “bubble-burst” current. The bubble burst current requirement [3] is that the injector current is to exceed Ψ^2_{inj}/ I_{tf}. Here Ψ_{inj} is the injector flux produced by the lower divertor coils and I_{tf} is the current in the toroidal field coil. The strong dependence of the required injector current on the injector flux and the weaker dependence on the current in the toroidal field coil has been verified in the HIT-II experiments and in previous NSTX experiments. For the highest injector flux values of interest in NSTX, based on previous experiments in NSTX, an injector current of up to 35 kA may be needed for transient CHI experiments. However at lower values of the injector flux, the injector current requirements are much less. A 2 kV, 50 mF capacitor bank that easily satisfies this requirement was designed and built for NSTX experiments.

The second requirement is related to how quickly the CHI discharge can fill the vessel, which depends on the applied injector voltage as this sets the rate at which toroidal flux moves across the injector and absorber gaps. For nominal NSTX conditions at 0.3 T on axis, there is about 1.4 Wb of toroidal flux inside the NSTX vessel. For 500 V across the injector electrodes, the time needed to displace all of the toroidal flux within the vacuum vessel is about 2.8 ms. Doubling the injector voltage will reduce this time to about 1.4 ms. Again, the quarter cycle pulse duration of the capacitor bank in NSTX satisfies this requirement.

The third requirement is that there should be sufficient energy in the capacitor bank to fully ionize and heat all of the injected gas. Typically about 50 eV is needed per ion for ionization and about 60 eV per ion to increase the plasma temperature to 20 eV. For experiments conducted during 2004, this condition was marginally satisfied because gas breakdown limits did not permit injecting less gas.

The fourth condition defines the maximum toroidal plasma current that can be produced in terms of the balance between inductive and capacitive stored energy: $\frac{1}{2}L_pI_p^2 = \frac{1}{2}CV^2$. The inductance of the toroidal plasma current on typical closed flux surfaces in NSTX is 0.5 to 1 μH, which for the NSTX capacitor bank size should provide a maximum toroidal current capability of over 400 kA.

A final requirement is that the flux “footprints” on the CHI electrodes should be sufficiently narrow. To produce this, currents need to be provided in the external poloidal coil system to maintain the CHI produced discharge in equilibrium. Poloidal coils in the vicinity of the injector provide this capability.

2. Recent NSTX hardware upgrades and experimental results

An initial test of transient CHI was conducted on NSTX during 2004. Toroidal plasma currents up to 140 kA were produced for injector currents of only 4.4 kA, representing a multiplication factor over 30. However, an unambiguous demonstration of closed flux beyond the end of the injection pulse was not achieved because the electron temperature, measured by Thomson scattering to be about 16 eV peak, was too low for the L/R decay time of the toroidal plasma current to exceed the RC decay time of the injector current. Three areas for improvement were identified: (1) doubling the injector voltage to 2 kV and improving the gas preionization to allow breakdown at lower gas pressure, thereby increasing the overall energy input per particle, (2) reducing the separation of the injector flux footprints on the electrodes to promote reconnection and detachment of the plasma, and (3) improving equilibrium control of the evolving discharge.

For experiments that commenced in 2005, a new pre-ionization method for initiation of CHI discharges at vessel gas pressures comparable to that used for normal inductive operation was successfully tested. In this method, after injecting < 7 x 10^{19} molecules of D_2 in the region below the lower divertor plates, 10 kW of 18 GHz ECH power was also injected in the cavity below the lower divertor plates. The ECH pre-ionized the injected gas resulting in a combination of neutral gas and ionized plasma entering the vessel through the lower divertor gap across which the capacitor bank voltage is applied. Toroidal field and gas pressure scans were conducted to determine optimum conditions for pre-ionization. As required, the pre-ionized plasma successfully coupled to and initiated a high current capacitor bank discharge. This is a factor of ten reduction in gas input compared to the minimum in 2004, an important condition needed to increase the energy per particle.

In order to rapidly quench the injector current after the CHI discharge has filled the vessel, a crowbar system has been installed this year and successfully tested. After the main ignitron switch is triggered to discharge the capacitor bank across the lower divertor electrodes a second ignitron is triggered after a suitable delay. This discharges the left over capacitor bank energy through a low (50 to 100 mOhm) resistor, causing the injector current to decay on a few ms time scale. Using a 25 mF capacitor charged to 970 Volts several discharges were produced with toroidal currents up to 100 kA. The current multiplication factors reached 60 at peak injector current and approached 170 towards the end of the discharge, approaching conditions necessary for the observation of toroidal current persistence after the injector current is reduced to zero. An example of such a discharge, from on-going experimental campaign is shown in Figure 2.

In summary, recent hardware improvements to NSTX are enabling generation of transient CHI discharges in NSTX which are very close to showing current persistence beyond the time duration of the injector current, which is a prerequisite before CHI produced discharges could be coupled to other current ramp-up methods.

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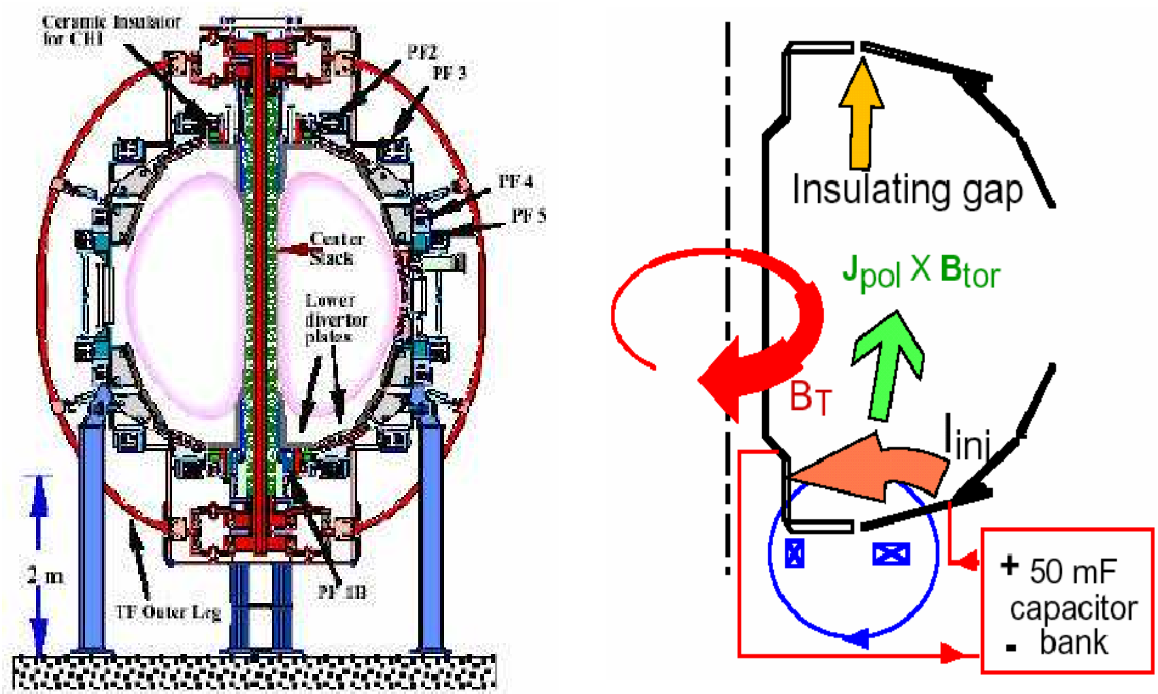

Figure 1: The NSTX Machine layout showing the locations of the upper and lower insulator rings which allow the inner divertor plates and center stack to be biased with respect to the outer components. Figure on the right shows how CHI is implemented in NSTX.

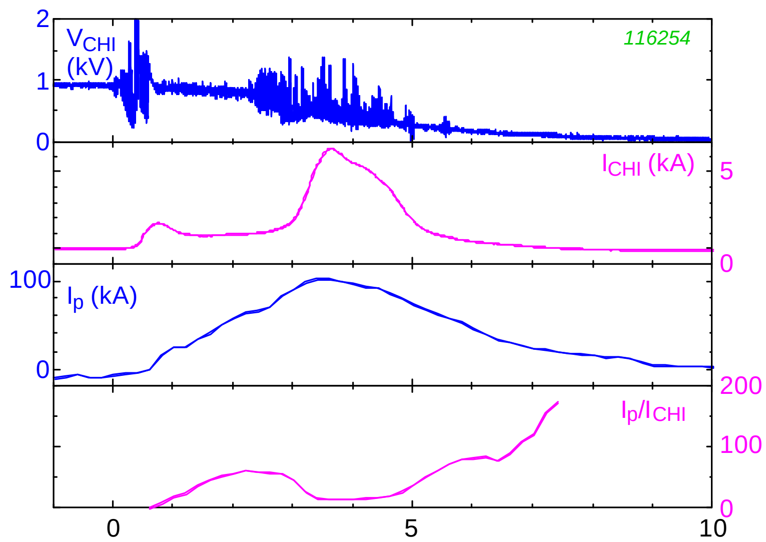

Figure 2: Recent Transient CHI discharge in NSTX. Shown are from top to bottom, the voltage across the injector (lower divertor) electrodes, the injector current, CHI produced toroidal current and the ratio of the toroidal current to the injector current. Note that the current multiplication increases as the injector current decreases, and reached values of up to 170.

[1] M. Ono et al., “Exploration of spherical torus physics in the NSTX device,” Nucl. Fusion **40**, 3Y 557 (2000).

[2] R.Raman et al., “Non-inductive solenoid-free plasma startup using CHI,” Nucl. Fusion **45** (2005) L15-L19

[3] T.R. Jarboe, “Formation and steady-state sustainment of a tokamak by coaxial helicity injection,” Fusion Tech. **15**, 7 (1989).