Transient CHI Solenoid-free Plasma Startup in NSTX*

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Abstract

Elimination of the central solenoid is a consideration for the design of toroidal confinement devices which will then require alternative methods for initiating the plasma current. A new method of non-inductive startup, referred to as transient coaxial helicity injection (CHI), has been successfully developed on the HIT-II experiment to produce 100kA of closed-flux toroidal current [R.Raman et al., Nucl. Fusion **45** (2005) L15-L19]. The method is now being tested in NSTX.

1. Requirements for Transient CHI

CHI is implemented on NSTX [1] by driving current along field lines that connect the inner and outer lower divertor plates. The inner and outer vessel components are insulated from each other by ceramic rings at the bottom and top. 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. 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.

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 [2] states that the injector current is proportional to Ψ^2_{inj}/ I_{tf}. 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 seen in the HIT-II experiments and in previous NSTX experiments. For the injector flux values of interest, based on previous experiments in NSTX, an injector current of up to 35 kA may be needed for transient CHI experiments. A 2kV, 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. This is dependent on the applied injector voltage as this sets the rate at which toroidal flux moves across the injector and absorber gaps. For nominal 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.

The fourth condition defines the maximum toroidal plasma current that can be produced in terms of the energy available from a given capacitor bank system: $^1/_2 L_p I_p^2 = {}^1/_2 CV^2$. The inductance of the toroidal plasma current on typical closed flux surfaces in NSTX is about 0.5 to 1 μH, which for the NSTX capacitor bank size should provide a maximum toroidal current capability of over 400kA.

A final requirement is that the flux footprints on the CHI electrodes should be sufficiently narrow and that currents need to be provided in the external poloidal coil system to maintain the CHI produced discharge in equilibrium. A newly designed poloidal coil on the inner vessel side and lower divertor coil provide this capability.

2. Recent NSTX hardware upgrades and experimental results

An initial test of this method 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 16eV 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 2kV 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 <2TorrL of D2 in the region below the lower divertor plates, 10kW 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 to enter 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 pressure compared to that possible in 2004, an important condition needed to increase the energy per particle.

In order to rapidly quench energy remaining in the capacitor bank after the CHI discharge has filled the vessel, a new crowbar system was successfully tested. In this system after the main ignitron switch is triggered to discharge the capacitor bank across the lower divertor electrodes, after a suitable time delay a second ignitron is triggered. This discharges the left over capacitor bank energy through a low (50 to 100 mOhm) resistor. This causes the injector current to be rapidly quenched on a few ms time scale. Then, using the lower divertor coils for flux footprint shaping and the upper coils for vertical stability control, using a 25mF capacitor bank charged to 970Volts several 100kA discharges were produced. Many of these had current multiplication factors of 60 and approached current multiplication factors of 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 campaigh is shown in Figure 1.

In summary, recent hardware improvements to NSTX is 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 pre-requisite before CHI produced discharges could be coupled to other current ramp-up methods.

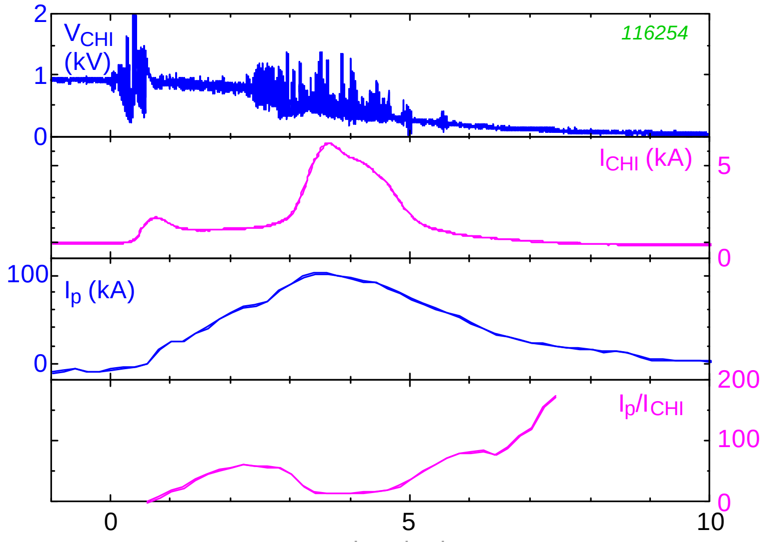

Figure 1: Recent Transient CHI discharge in NSTX. Shown are from top to bottom, the voltage across the injector (lower divertor) electrodes, the injector current, CHI produced toroidal current and the ratio of the toroidal current to the injector current.

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