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Demonstration of 300 kA CHI-startup current, coupling to transformer drive and flux savings on NSTX

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Abstract

Discharges formed by transient coaxial helicity injection (CHI) in the National Spherical Torus Experiment (NSTX) have attained peak currents of 300 kA for the first time. CHI-started discharges are coupled to induction, and ramped up to over 1 MA. Up to an additional 400 kA of toroidal current is produced, compared with discharges with the same inductive drive without CHI. These CHI-inductively coupled discharges demonstrate flux savings over standard NSTX inductive-only discharges, requiring significantly less transformer flux to reach 1 MA of toroidal current, as well as exhibiting higher elongation and lower internal inductance. These results indicate the potential for substantial current generation capability by CHI in NSTX and in future toroidal devices.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The spherical torus [1] (ST) is a low aspect-ratio toroidal magnetic confinement concept featuring the advantages of high beta and a high fraction of bootstrap current. Because of the low aspect ratio, elimination of the central solenoid is very important for the next generation of ST experiments and is essential for the viability of the ST concept as a reactor. Non-inductive methods for plasma current startup and sustainment therefore become necessary. An alternate method for plasma startup could also reduce the cost of a future tokamak reactor as indicated by the ARIES design studies [2]. The National Spherical Torus Experiment (NSTX) is exploring the technique known as coaxial helicity injection (CHI) [3] as a method to produce the initial plasma and sufficient toroidal plasma current to allow other methods of non-inductive current generation and sustainment to be applied.

CHI is a promising candidate both for plasma startup and for edge current drive during the sustained phase. The possibility of using CHI in an ST was first proposed in the late 1980s [3]. Helicity injection current drive (with a biased electrode) in a ST was first conducted on the Current Drive Experiment-Upgrade (CDX-U) at the Princeton Plasma Physics Laboratory (PPPL) [4]. CHI in an ST was pioneered by experiments conducted on the Proto-Helicity Injected Torus, and the Helicity Injected Torus-I (HIT-I) at the University of Washington [5]. These HIT experiments used a thick conducting copper wall for equilibrium control of the CHI-produced plasma configuration. Two other experiments that used CHI are the Helicity Injected Spherical Torus (HIST) in Japan [6] and the SPHEX device in the UK [7]. These devices also employed passive wall stabilization for equilibrium control and confirmed that CHI could be used in the presence of an external toroidal field for the generation of a plasma configuration. Later HIT was rebuilt as the HIT-II experiment, which extended CHI to a true ST device by employing poloidal field coils for equilibrium control and transformer action [8]. Later the method was adapted to the NSTX device, which employs standard tokamak components [9].

It is generally accepted [10] that non-axisymmetric plasma perturbations are needed for long-pulse current drive ($t_{\rm pulse} > t_{L/R}$), where the CHI injector circuit is continuously driven. This mode of CHI, also referred to as steady state, or driven CHI, was the method initially tried on NSTX and used on other devices [11, 12]. A significant recent development is the demonstration of a new mode of CHI operation on an ST,

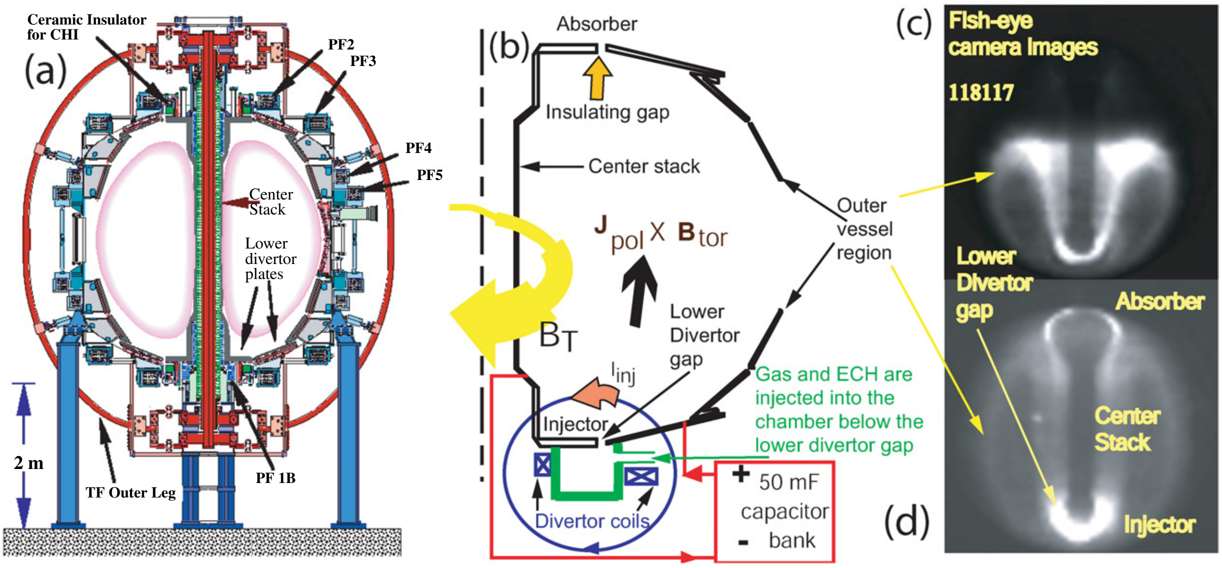

Figure 1. NSTX machine layout showing the location of the toroidal insulator and external poloidal field coils. (*b*) Components used for CHI startup in NSTX and (*c*) fast camera fish eye images showing discharge evolution from near the injector region and (*d*) later during the discharge.

referred to as transient CHI [13], analogous to fast formation ($t_{pulse} \ll t_{L/R}$) on spheromaks [14, 15]. Transient CHI appears to involve axisymmetric (or nearly axisymmetric) reconnection and was highly successful on the HIT-II experiment. While the steady-state approach is still needed for sustained edge current drive, transient CHI has been extremely successful on HIT-II for plasma startup. Recent results from the successful application of transient CHI on NSTX are described in the subsequent sections.

Results presented here include characteristics of higher current CHI-startup plasmas, their subsequent coupling with inductive current drive, and flux savings. These results show the suitability and capability of CHI-startup plasmas with high-performance (1 MA) discharges in NSTX.

2. Implementation of CHI on NSTX

Implementation of CHI on NSTX draws on extensive experience from the HIT and HIT-II experiments at the University of Washington, and work elsewhere [8–20]. The NSTX device is described in [21]. To accommodate CHI, the NSTX stainless-steel vacuum vessel (nominal major radius 0.85 m, volume 30 m^3) has separate inner and outer sections, electrically isolated from each other by toroidal ceramic rings at the top and bottom which also act as vacuum seals. The inner divertor plate (part of the centre stack assembly) is thus electrically separated from the outer divertor plate, which itself is electrically connected to the outer vessel, as illustrated in figures 1(*a*) and (*b*). The poloidal field coils located beneath the lower insulated gap are used to produce poloidal flux connecting the lower inner and outer divertor plates, as indicated qualitatively by the (purple) circle in figure 1(*b*). The lower gap connected by the poloidal field is referred to as the injector and the complementary upper gap as the absorber (as when voltage is applied, toroidal flux flows out of the injector and into the absorber [3]). A small amount of deuterium gas is introduced into the chamber, then a voltage (typically 1–2 kV) is applied between the plates, forming a discharge with plasma current flowing from the outer divertor plate to the inner lower divertor plate, as shown by the lower brown arrow in figure 1(*b*). In the presence of a toroidal field, the plasma current, which essentially flows along field lines, develops a toroidal component. The bright region at the top of figure 1(*c*) is the top of the CHI plasma that has extended to approximately the middle of the vessel, before peak current. As the plasma current increases to near the peak value, the discharge further elongates to fill the vessel as shown in figure 1(*d*). The bright ring-shaped region at the top of this image is referred to as an absorber arc, a condition when part of the injector current flows across the upper divertor gap.

The toroidal plasma current produced by CHI initially flows on open field lines joining the electrodes. To produce toroidal plasma current on closed flux surfaces, either magnetic reconnection or dynamo activity occurs. In steady state, this current drive depends on non-axisymmetric plasma perturbations. For transient CHI, the initial poloidal field magnitude is chosen such that the plasma carrying the injected current rapidly expands into the chamber. As the CHI capacitor bank charge is depleted, the injected current rapidly decreases, and axisymmetric magnetic reconnection can occur near the injector electrodes, with the toroidal plasma current forming closed-flux surfaces. The method of transient CHI has been successfully used on NSTX for an unambiguous demonstration of closed-flux current generation (namely a persistent I_{tor} after $I_{inj} = 0$) without the use of the central solenoid [22]. The CHI capacitor bank has several requirements on current, voltage, energy and current multiplication, which are discussed in detail in [23, 24].

3. Improvement of CHI-only and CHI-inductive coupling by impurity reduction

CHI-startup-only discharges in NSTX have reached up to 300 kA with ratios of I_{tor} to I_{inj} in the range 50–70.

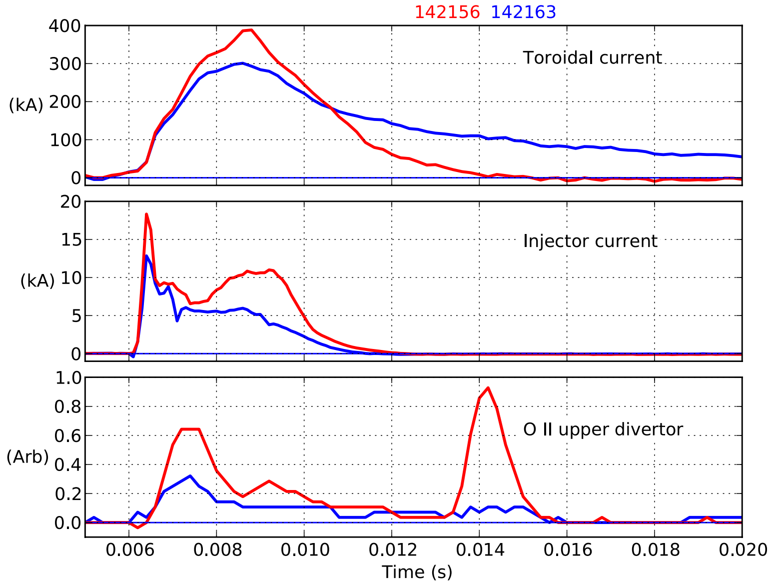

Figure 2. Toroidal plasma current (I_{tor}), CHI injector current (I_{inj}) and upper divertor O II emission for two CHI-only discharges, one with a 20 mF bank (blue) and one with 30 mF (red). The red trace reaches a higher current, but had an absorber arc, decreasing its current multiplication factor and limiting its lifetime.

This is achieved using a larger capacitor bank and careful reduction of low-Z impurity production (primarily oxygen and carbon). Several methods to reduce impurities are available: (1) CHI electrode conditioning (operating a dc CHI supply for long pulses with high injector flux), (2) deuterium glow discharge cleaning (to chemically sputter impurities), (3) use of 'absorber coils' to reduce interaction between the expanding CHI plasma and the upper divertor and (4) lithium evaporation onto the lower divertor, using the NSTX LITER system [25].

Figure 2 shows I_{tor}, I_{inj} and upper divertor O II emission for two discharges. The discharge with higher peak current used a 30 mF CHI capacitor bank (6 capacitors) and the lower current discharge used a 20 mF bank (4 capacitors). Peak values of $I_{tor} \simeq 300$ kA are observed, with well over 200 kA of closed-flux current remaining after $I_{inj} \simeq 0$. The higher current trace of figure 2 is a discharge with an absorber arc; note I_{inj} has a 'spike' at the beginning, resulting in much higher impurity radiation, especially at the upper divertor (absorber) region. Although I_{tor} reaches a higher peak, the closed-flux current decays much more quickly than discharges without an absorber arc.

Even though the higher current discharge had an arc and a resulting faster current decay time, this discharge indicates the initial current generation capability in the 350–400 kA level in NSTX. Future experiments will use higher levels of current in the absorber coils to avoid the absorber arc under these conditions. Furthermore, these discharges did not utilize full lithium coverage of the lower divertor plates. With improvements in these areas, reproducible discharges at this current level with good current persistence could be expected in NSTX.

Figure 3 shows the improvement of CHI-startup coupling to transformer drive with better optimized equilibrium boundary conditions and higher absorber coil currents. Discharges from the previous (2009) campaign, 135614

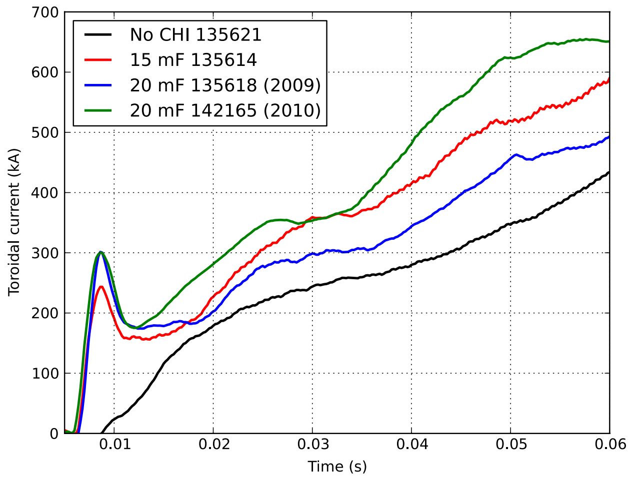

Figure 3. Plasma currents for CHI-startup coupled to transformer drive, showing performance improvement with improved equilibrium and absorber coil control. Discharge 135614 used a 15 mF bank, and discharge 135618 used a 20 mF bank, the latter having an absorber arc. Discharge 142165, with better coil programming and higher current in the absorber PF coil, used 20 mF, reaching over 600 kA at $t = 50$ ms, approximately 100 kA higher than discharge 135614, the best CHI-startup discharge generated in 2009. (A reference transformer-only discharge, 135621, is shown for comparison.)

and 135618, used 15 mF and 20 mF CHI capacitor banks, respectively. Discharge 135618, with 4 capacitors, had a larger peak CHI current, but also an absorber arc, and lower ultimate current. In the 2010 campaign, with better equilibrium programming and absorber arc control via the absorber coils, discharge 142165 (27 kJ energy bank) reached 650 kA at $t = 50$ ms, much higher than from the previous campaign. (Discharge 135621 is a reference transformer-only discharge with the same loop voltage programming.)

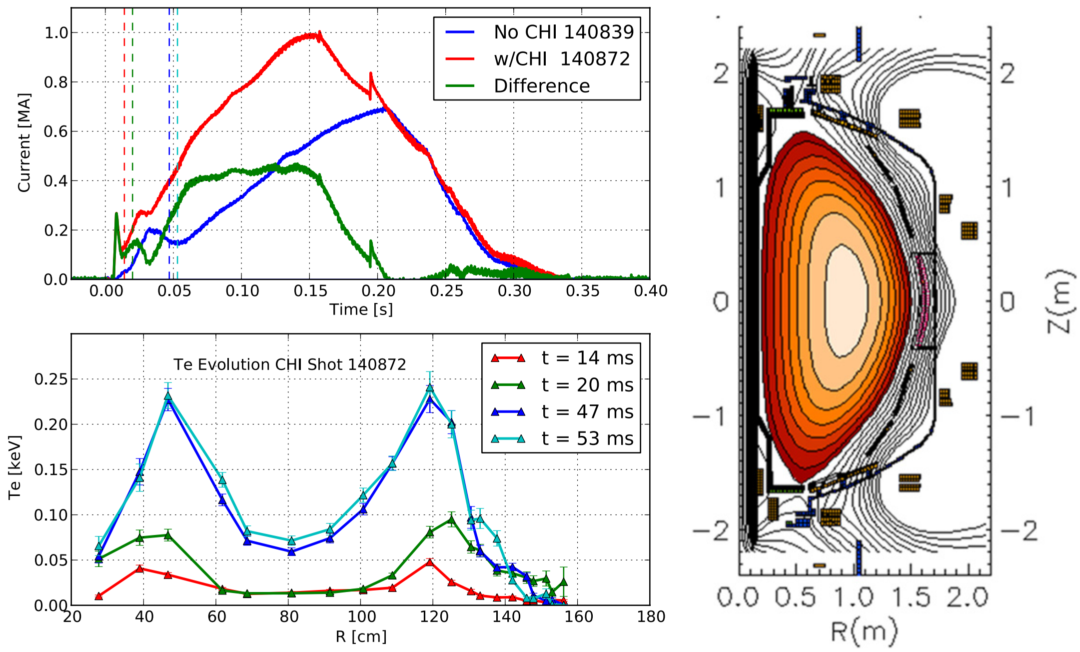

Figure 4. Top left: the red trace is a discharge started with CHI (at 6 ms) and coupled to induction reaching 1 MA at 150 ms. The comparison discharge (blue trace) using the same loop voltage programming, without CHI startup reaches only 600 kA at the same time. The green trace shows the difference in current between the two discharges. Bottom left: electron temperature profiles at various times at midplane ($Z = 0$). Right: EFIT reconstruction of discharge 140872 at 100 ms. (Courtesy: S. Sabbagh).

4. CHI-startup flux savings over standard inductive-only discharges

The most recent experiments in which CHI initiation was followed by inductive ramp-up produced final currents exceeding 1 MA using only 0.28 Wb of the 0.33 Wb of the inductive flux available from a uni-directional swing of the central solenoid. This is the highest current produced in NSTX using this amount of central solenoid flux without auxiliary heating, and is a significant improvement over the 800 kA achieved using all of the flux from a single swing of the central solenoid in 2009 and described in [26]. The improvements were obtained by more effective use of the absorber coils to reduce absorber arcs, and reducing impurities originating from the CHI electrodes by increased use of lithium coatings. Coupling of CHI-started currents to induction and ramping to high current in this campaign was possible using up to 5 capacitors. Figure 4 is a comparison of two discharges, one with CHI startup coupled to induction and the second with induction only (with the same loop voltage programming).

The electron temperature during the transition phase from CHI to induction (around 20 ms) reached over 100 eV in many shots. The shots with such high early electron temperatures ramped up to the highest currents. At 50 ms, a peak temperature of nearly 250 eV is reached off-axis with core electron temperatures of 70 eV. The hollow electron temperature profile characteristic of CHI startup is now retained during most of the current ramp. Figure 4(*b*) shows an equilibrium reconstruction at 100 ms which uses Thomson scattering electron temperature and density profiles and the measured diamagnetic flux as constraints on the pressure profile. High initial electron temperatures are correlated with successful coupling to inductive ramp up.

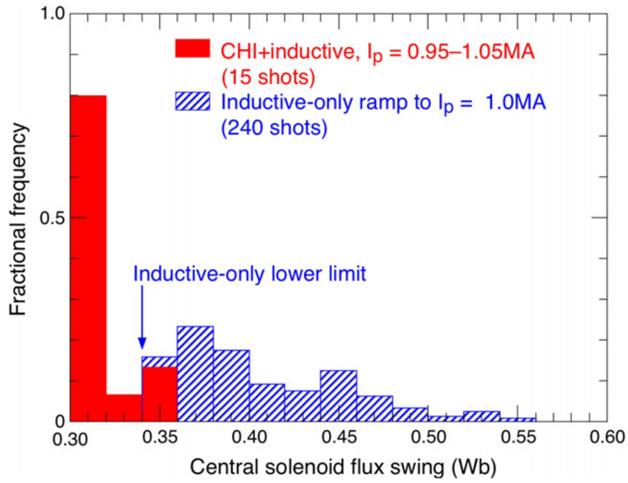

Figure 5. Fractional frequency of NSTX discharges reaching 1 MA versus central solenoid flux swing. The red/solid bars are for CHI-inductively coupled plasmas, and the blue/hashed bars are for standard NSTX NBI-heated H-mode plasmas.

CHI-inductively coupled discharges require less transformer flux to reach 1 MA when compared with *standard* NSTX inductive-only H-mode NBI discharges, figure 5. ('Standard' NSTX discharges use I_{tor} feedback control, rather than the pre-programmed loop voltage waveform used during the CHI-inductive studies.) Figure 5 shows that for 15 CHI-started discharges, a large majority (12) required only about 0.3 Wb of flux swing to reach 1 MA. For standard inductive-only NSTX discharges, the smallest amount of flux swing required was 0.34 Wb (for ~15% of shots) and typically required much more flux (sometimes over 0.5 Wb).

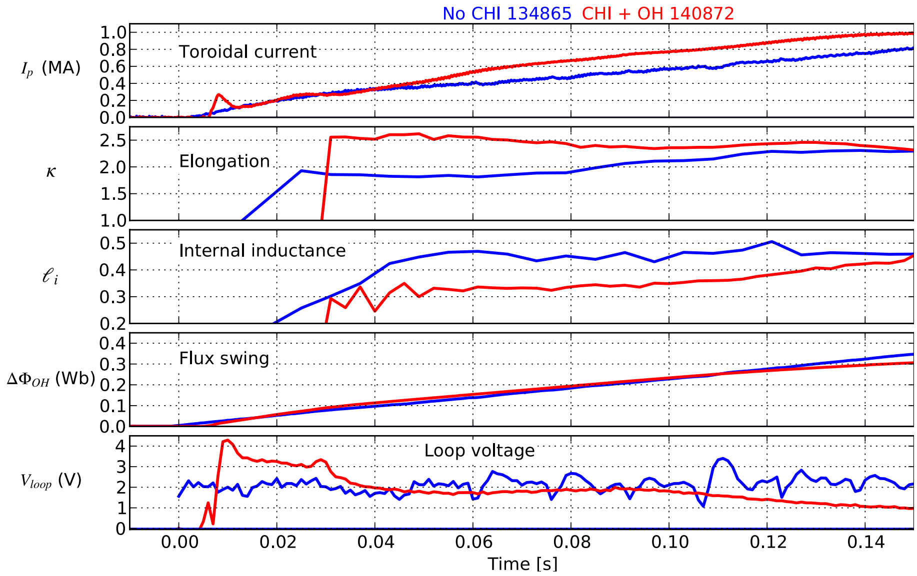

Figure 6. Comparison of a CHI-startup plasma coupled to inductive drive with a standard NSTX NBI-heated H-mode plasma. The CHI-started discharge reaches 1 MA using less transformer flux, and EFIT equilibrium fitting shows higher elongation (κ) and lower internal inductance (ℓ_i).

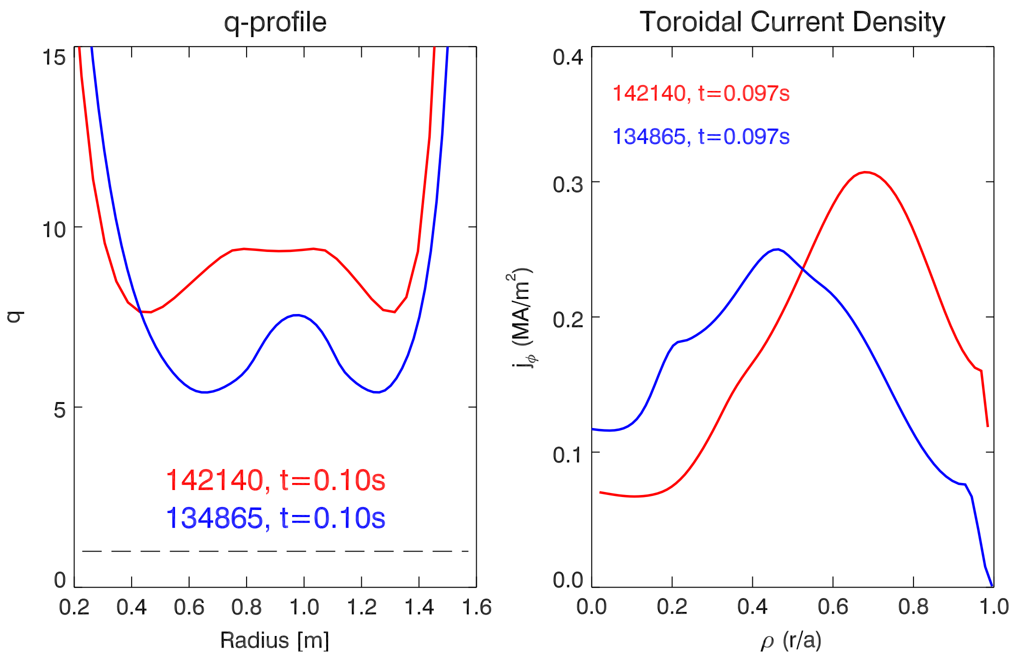

Figure 7. Comparison of safety factor (q) and toroidal current density (J_{tor}) profiles at $t = 100$ ms for a CHI-inductively coupled plasma (red) and a standard inductively driven NSTX plasma (blue).

Due to the method of closed-flux formation, CHI-startup plasmas have both a very high elongation of $\kappa \sim 2.6$ and a hollow electron temperature profile. After the rapid inductive ramp, very low internal inductance $\ell_i \sim 0.3$ (as calculated by the EFIT equilibrium-fitting code [27]) is seen from the start of the discharge, as shown in figure 6. CHI uses more loop voltage at the start, but after 50 ms, less than the standard case. Beyond 150 ms, the loop voltage for the CHI case is too low to drive the 1 MA discharge. (The standard OH discharge has high loop voltage even at 150 ms because it used a double swing of the transformer flux.) At about 120 ms, both discharges have approximately the same flux swing, but the CHI case produced much more current. The low inductance indicates a hollow current profile, shown in equilibrium reconstructions. The mechanisms responsible for maintaining these hollow profiles during the OH ramp are the subject of ongoing studies.

Figure 7 shows safety factor (q) and toroidal plasma current density (J_{tor}) profiles from equilibria fits including MSE data for CHI-startup and inductive-only discharges at $t = 100$ ms. The CHI-startup plasmas show a larger edge current than inductive-only plasmas. Also, these plasmas are relatively free of MHD activity despite having low density, which has previously been associated with increased instability during normal inductive startup.

5. Summary and future plans

Transient CHI in NSTX produces nearly 300 kA of startup current and is coupled to induction, reaching 1 MA, over 400 kA higher than discharges with the same loop voltage programming without CHI. Impurity reduction methods, including surface conditioning and flux boundary conditions, have allowed successful coupling using larger CHI capacitor banks, and is correlated with increased electron temperature during the transition from CHI to transformer drive. CHI-started, inductively ramped 1 MA discharges use less transformer flux compared with a database of standard NSTX inductive-only current-drive plasmas. CHI-startup discharges show higher elongation (κ) and lower internal inductance (ℓ_i) than standard discharges.

Future plans include coupling of inductive drive to a larger number of capacitors in the CHI bank to achieve higher transition currents, coupling to non-inductive current-drive techniques, such as high-harmonic fast wave, and exploration of the high-κ, low-ℓ_i plasmas produced by transient CHI, which are of considerable interest to advanced scenario operations.

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