

$E \times B$ Plasma Rotation and $n = 1$ Oscillation Observed in the NSTX-CHI Experiments

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In the National Spherical Torus Experiment (NSTX), a peak plasma current up to 390 kA has been successfully generated by the Coaxial Helicity Injection (CHI) current drive method. The plasma rotation (~ 20 km/s) driven in the $E \times B$ toroidal direction by CHI has been clearly identified by an ion Doppler spectroscopic measurement. The $n = 1$ mode has been also observed to rotate in the same direction. This rotating kink behavior observed for the first time in NSTX is consistent with the electron locking model developed in the Helicity Injected Torus-II (HIT-II) experiments to explain the mechanism of CHI current drive.

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Coaxial helicity injection is one of most attractive candidates to resolve the non-inductive current-drive and plasma start-up issues for spherical torus (ST) [1, 2] and spheromak [3]. CHI has been used to successfully produce non-inductive discharges with up to 390 kA of toroidal current in 0.330 s long pulse in the NSTX device [4] at the Princeton Plasma Physics Laboratory (PPPL). During the steady-state CHI operation, a current transfer mechanism relied on MHD relaxation is required to generate closed flux and its identification has been a subject of ongoing research. An electron locking model [1] was proposed as a possible mechanism for current drive with CHI and its validity was confirmed by accounting for experimental observations in the HIT-II device [1]. The two key elements in the model are 1) $n = 1$ helical magnetic distortion at the edge coupling the open flux to the closed flux, and 2) the toroidal plasma rotation due to $E \times B$, where B is the poloidal magnetic field at the plasma edge. The rotating helical distortion across the separatrix is predicted to convect some of the electron fluid into the closed flux region, resulting in current drive. This paper shows that the $E \times B$ plasma rotation along with the $n = 1$ distortion is verified by ion Doppler spectroscopic measurements for the long pulse high current discharge demonstrated on NSTX. This result obtained on the NSTX is consistent with observations on the HIT-II.

The NSTX device parameters are: major/minor radii of 0.85/0.65 m, elongation ≤ 2.5 , plasma volume 12.5 m³

[5]. The NSTX vacuum vessel is split in two using toroidal ceramic breaks at the top and bottom to electrically insulate the central column and the inner divertor plates from the outer wall and the outer divertor plates as shown in

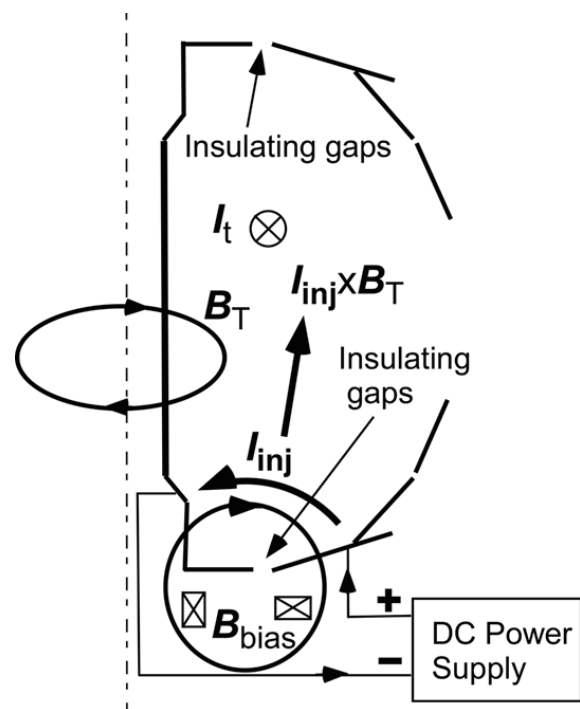


Fig. 1 Schematic showing application of CHI in NSTX

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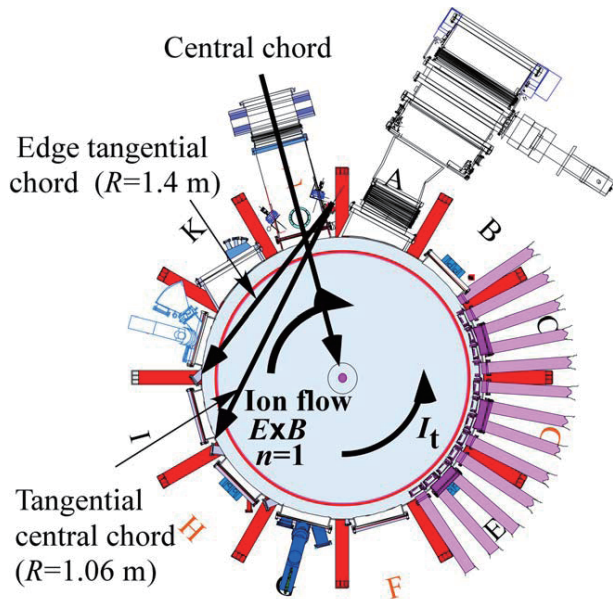


Fig. 2 A top-down view of the NSTX machine showing the three chords used for the IDS measurements.

Fig. 1. The CHI voltage V_g is applied to the inner (cathode) and outer divertor plates (anode) and a pre-programmed amount of gas is then injected from four ports located on the inner divertor plates. Current is then driven along magnetic field lines that connect the lower divertor plates. A DC power supply (50 MW) was used at less than 1 kV to provide the injector current of 20–28 kA.

Measurements for ion Doppler temperature and the toroidal plasma rotation velocity were performed using the Ion Doppler Spectrometer (IDS) VIPs-2 0.5 m-spectrometer (Acton Research Spectra Pro 500i) to look spectral lines in the range of 200–700 nm. The time resolution of the system is 0.026 s and the wavelength resolution is 0.012 nm/pixel. Instrumental error of the ion temperature is ~ 4 eV. The central chord, the central tangential chord ($R = 1.06$ m) and the edge tangential chord ($R = 1.4$ m) are simultaneously available as shown in Fig. 2. The C III impurity spectral line (464.74 nm) was mainly used for the IDS measurements.

The toroidal current I_t generated by CHI increases up to 390 kA as shown in Fig. 3 (a). The observed $n = 1$ mode initiates at about 0.18 s when the toroidal current rapidly increases to nearly 400 kA and also the injector current increases to ~ 28 kA from ~ 20 kA as the bias flux B_{bias} is decreased. The plasma decays quickly at around 0.24 ms due to its resistivity after the injector voltage is turned off. Figures 3 (b) and (c) show the CIII ion flow speed $v_{i,\phi}$ and temperature $T_{i,D}$ from CIII Doppler data obtained at the three chords, respectively. $T_{i,D}$ at the central tangential chord increases to about 30–60 eV. $T_{i,D}$ at the central and edge tangential chords are in the range of 20–40 eV. We have found that the CIII ion flow rotates in the opposite

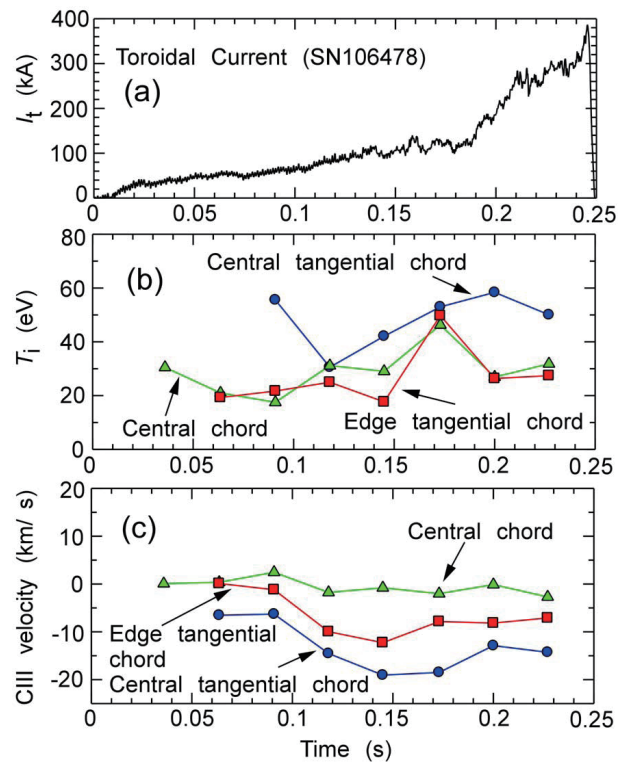


Fig. 3 Time evolution of the toroidal current I_t (a), Doppler ion temperature $T_{i,D}$ (b) and CIII ion flow velocity (c).

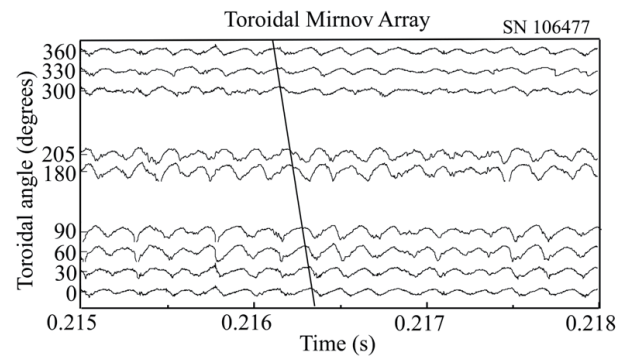


Fig. 4 Toroidal Mirnov coil signals as functions of time and coil position, showing regular oscillations of approximately 5 kHz are generated by CHI and propagate toroidally with $n = 1$ mode.

direction to the plasma current, but in the same direction as the applied $E \times B$. The peak velocity measured at the central tangential chord is $v_{i,\phi} \sim 20$ km/s between $t = 0.14$ and 0.18 s. The plasma rotation frequency estimated from the ion flow speed is about 3 kHz at $R = 1.06$ m. The direction of the observed $n = 1$ mode propagation, as shown in Fig. 4, matches that of the edge $E \times B$ flow direction. The $n = 1$ mode activity was observed reproducibly. The rotation speed of the $n = 1$ distortion is roughly the same as the speed of plasma rotation. This result is consistent with the prediction of the electron locking model, which requires

that the $n = 1$ mode speed should match the $\mathbf{E} \times \mathbf{B}$ drift speed, i.e. the plasma rotation speed. This model was verified in the HIT-II device by reversing the central column polarities (see chapter 3 in Ref. [1]).

Experiments on NSTX have succeeded in attaining 390 kA of CHI generated toroidal current without relying on the ohmic solenoid. CHI discharges are characterized by $T_{i,D} = 20\text{--}60$ eV and the $\mathbf{E} \times \mathbf{B}$ plasma rotation with the $n = 1$ distortion with the speed of ~ 20 km/s. An improved understanding of CHI current drive mechanism

is being developed using measurements from the IDS and edge magnetic field diagnostics.

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