Current Drive Experiments on the HIT-II Spherical Torus

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The goal of the Helicity Injected Torus (HIT) program is the study and development of helicity injection current drive in magnetically confined low-aspect-ratio toroidal plasmas [1,2]. HIT-II is a modestly sized spherical tokamak (major radius R=30cm, minor radius a=20cm, on-axis toroidal field up to 0.5 T) capable of using either Coaxial Helicity Injection (CHI) or inductive (Ohmic) drive to create and sustain toroidal current. Using either CHI or Ohmic separately, HIT-II has demonstrated peak plasma currents of more than 200 kA.

A unique feature of the HIT-II device is its real-time flux feedback control system [3]. This system uses a set of 28 Poloidal Field Coils (PFCs), 14 of which are located in the central column and 14 on the outer shell. The current in each PFC is independently controlled, and adjusted so that the poloidal flux measured by a nearby loop matches a pre-programmed demand. This feedback system responds to changes in the boundary flux due to plasma dynamics in a fraction of a millisecond, and is capable of preventing or controlling axisymmetric plasma displacements. The flux demand functions can be engineered either to generate local flux conditions (*e.g.*, a divertor) or to act effectively as a transformer, by driving poloidal flux into the shell at a specified rate (*i.e.*, a precisely defined loop voltage).

Ohmic plasma performance in HIT-II has been optimized recently, producing discharges with durations greater than 55ms and peak toroidal currents near 200 kA. Figure 1 shows a recent high-performance limited Ohmic discharge, shot #20651, generated using a 60mWb Ohmic flux ramp. Note the applied loop voltage is approximately 2V during the majority of the current rise, indicating a low impurity-ion content. The bursts of toroidal-field fluctuations during the current ramp-up and decay correspond to current-profile relaxation events, which have been studied in some detail in HIT-II [4] and other STs.

Recent CHI experiments on HIT-II use an unbalanced Double-Null Divertor (DND) flux boundary configuration. Discharges formed and sustained in this DND configuration exhibit better plasma performance than previous single-null boundary results: less shorting current in the region of the absorber; a higher injector-current amplification ratio I_p/I_{inj}; better shot-to-shot reproducibility; and, lower levels of impurity line radiation. The remaining impurity line radiation in DND discharges tends to correspond to higher charge states, indicating a better "burn-through" of the low charge states. Finally, the DND plasmas exhibit a robust, high frequency n=1 mode at the outboard edge; the presence of this mode has been empirically correlated with current-profile relaxation and high performance in CHI discharges in the HIT, HIT-II, SPHEX and NSTX devices [5]. Shot-to-shot variations in the amount of the injector flux show that injector current in DND discharges is approximately proportional to the square

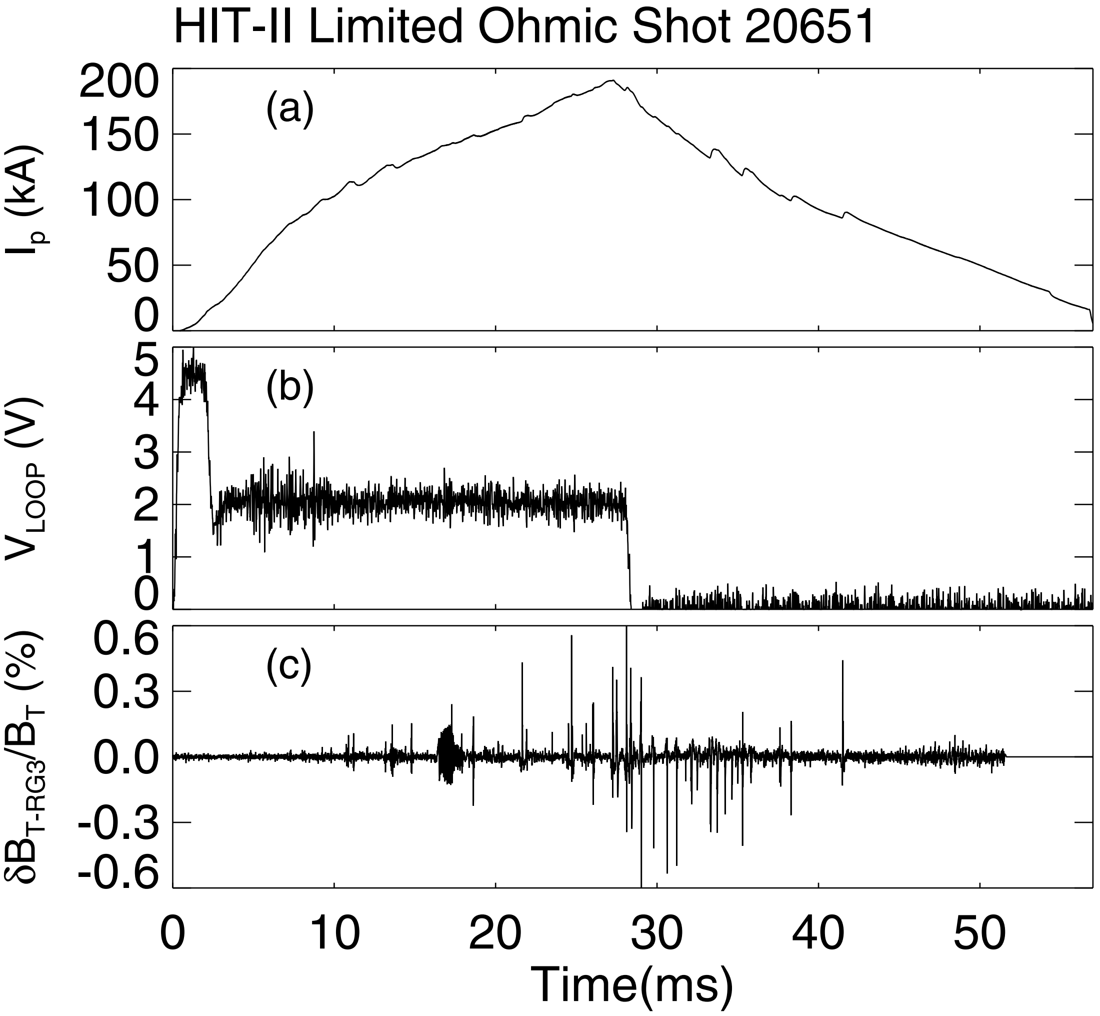

Figure 1: (a) Plasma current, (b) Applied loop voltage and (c) Toroidal field fluctuations for the HIT-II limited Ohmic discharge #20651.

of the injector flux, as expected in CHI current drive [2]. From shot-to-shot variations in the time dependence of the injector voltage, the total CHI-driven plasma current is inferred to be proportional to the helicity injection rate, $\psi_{inj}V_{inj}$, where ψ_{inj} is the injector flux. Figure 2 shows both an equilibrium cross-section (from an EFIT reconstruction to magnetic data [6]) for a DND CHI discharge in HIT-II, and time traces for an identical DND discharge. Note that, in the EFIT reconstruction, there is a thin vacuum region between the plasma and the conducting wall everywhere but in the injector, and that the only open flux interacting with the conducting wall is also being driven by the CHI electrodes in the injector. These features of DND discharges are essential for high performance, reducing the impurity-ion content and ensuring the presence of a robust n=1 mode.

A model has been developed for the detailed physical mechanism governing helicity injection current drive. This model is found to be consistent with experimental observations of CHI plasmas in the HIT and HIT-II devices, under a variety of conditions. This model depends upon the observation that an ST plasma in HIT geometry, with a hollow current profile and a rational-q surface in a thin (1-10mm) vacuum region, is unstable to an n=1 external kink mode, even in the presence of significant magnetic shear [7]. This kink mode, driven by the free energy in the gradient of the hollow current profile, propagates on the resonant-q surface

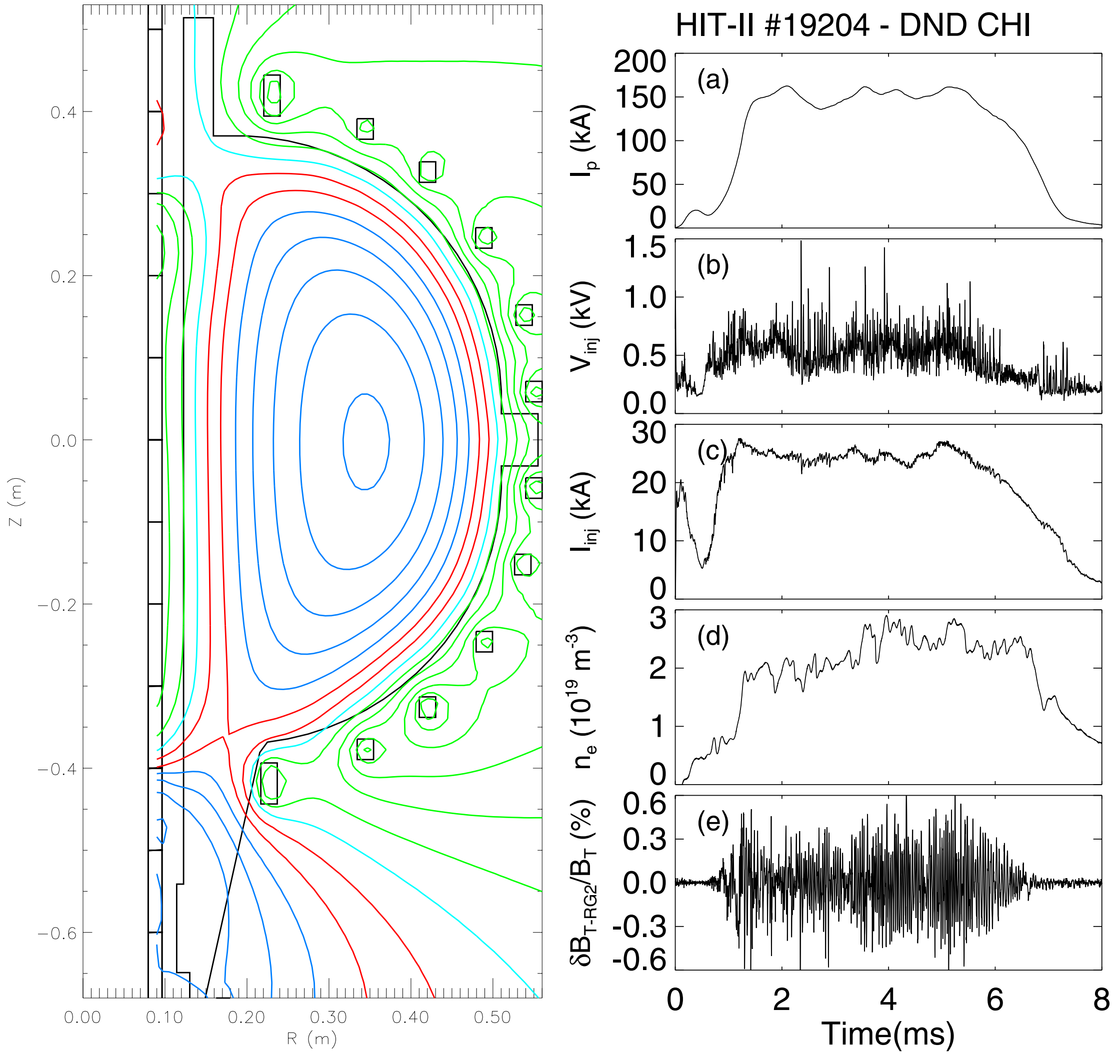

Figure 2: At left, an EFIT equilibrium reconstruction for HIT-II DND CHI discharge #19179 at time 4.2ms. At right, (a) Plasma current, (b) Injector voltage, (c) Injector current, (d) Electron density and (e) Toroidal field fluctuations for DND CHI discharge #19204.

in the *ExB* direction, perpendicular to both the electron fluid drift and the radial coordinate. If the mode's radial structure is distorted by the differential rotation of the electron fluid (where this distortion is modeled most simply as a phase, proportional to the square of the radial distance from the resonant surface), then the fluctuating magnetic energy of the mode is converted into toroidal current drive. This toroidal drive (current drive inside the resonant surface, current anti-drive outside) flattens the gradient in the current density profile, reducing the free energy. Externally driving current outside the resonant surface (with CHI electrodes, for instance) enables the plasma to reach a steady state: the driven edge current produces a hollow current profile, driving an n=1 kink mode on a resonant surface, in turn producing toroidal current inside that resonant surface.

There are subtleties regarding the location of the n=1 mode activity and the polarity of the central electrode, described in Ref. [8]. This mechanism is consistent with significant current drive in a CHI tokamak only in cases where the central electrode is a cathode. If a CHI tokamak is operated with an anode Central-Column (CC), it is expected that the current drive near the resonant surface by the n=1 mode will have the opposite sense. That is, the n=1 mode will drive current outside the resonant surface, filling the vacuum region with toroidal

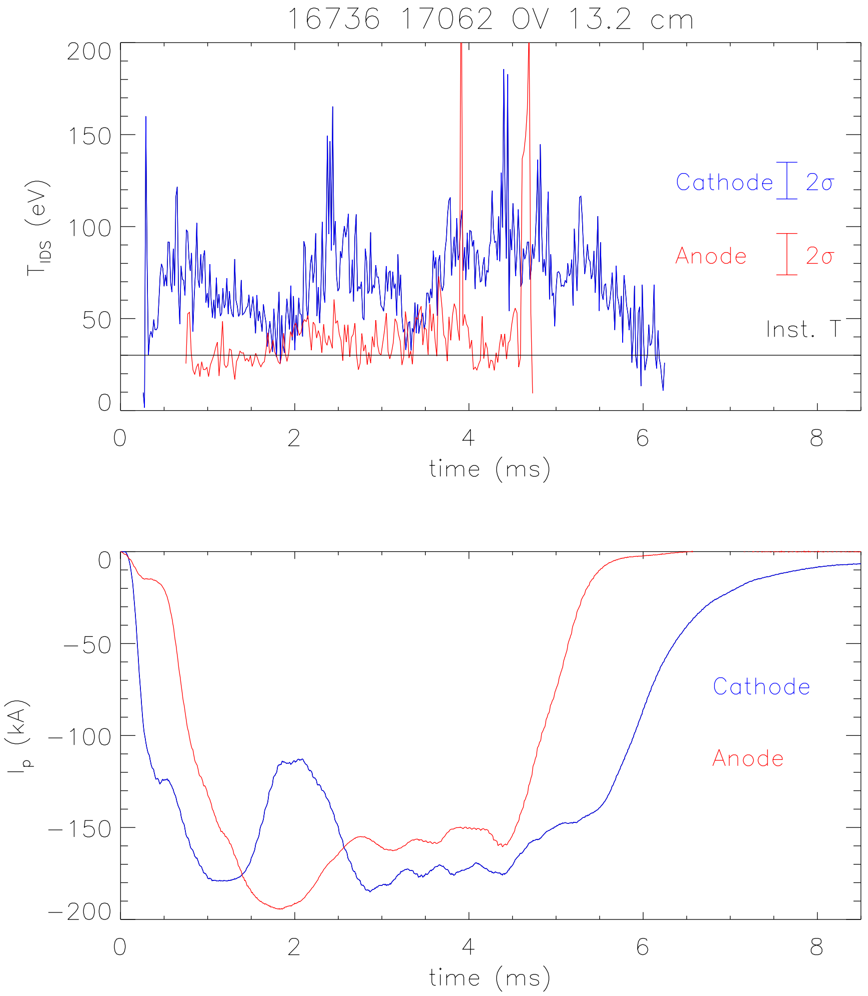

Figure 3: Chord-averaged ion temperatures, as measured by Ion Doppler Spectroscopy (IDS), and toroidal plasma currents for comparable cathode-CC and anode-CC discharges in HIT-II. The ion Doppler diagnostic monitored Oxygen-V emission on a chord with impact parameter 13.2cm.

current and stabilizing the kink mode. Significant differences in behavior and performance between cathode-CC and anode-CC plasmas are to be expected. Experimentally, cathode-CC CHI plasmas in HIT-II have more robust n=1 modes, more relaxed (less hollow) current density profiles, and more bulk ion heating than comparable anode-CC plasmas. Figure 3 shows ion temperatures for a comparable pair of cathode-CC and anode-CC single-null CHI discharges on HIT-II. Note that the temperature of the anode-CC plasma does not rise significantly above the “instrument temperature” of the diagnostic, while the temperature of the cathode-CC plasma ranges between 50eV and 100eV throughout most of the discharge.

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